The Development of a Rapid Prototyping Selection System for Small Companies.

within the discipline of Design

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This dissertation is being submitted in fulfilment for the requirements for the Degree of Doctor of Philosophy for the University of Wales.

June 1999
Declaration

This dissertation is the result of my independent research. Where it is indebted to the work of others, acknowledgement has been made.

I declare that it has not been accepted for any other degree, nor is it currently being submitted in candidature for any other degree.

I hereby give consent for my dissertation, if accepted, to be available for photocopying and for inter-library loan, and for the title and abstract to be made available to outside organisations.

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Abstract

This research describes the development of a computer based design advice system intended specifically to aid small companies in the application of rapid prototyping. To accomplish this firstly required a thorough review of the current state of the art in prototyping technologies and associated processes. Through interviews with industry professionals this review included an assessment of the actual operational capabilities found in industry as opposed to theoretical performance measures. From this data, rules were created to quantify and rank the performance of the different technologies according to parameters that are the most readily available and easily understood by the user. It was also necessary to devise a method of specifying the users' requirements of the prototype.

Providing as much automation as possible, required the development of software capable of reading in CAD data and deriving from it the parameters that would most affect the suitability of a rapid prototyping process. Further software was developed to calculate realistic and reliable estimations for the costs and lead times associated with different possible routes.

Explanatory material was added to the system to describe and illustrate how the different technologies worked, such that with continued use, the user could become familiar with rapid prototyping.

Unlike previous attempts at producing a rapid prototyping selection system, the one described here was tested with target users and verified against the opinion of an industry expert. The resulting system was found to be quick and simple to operate providing all of the required information whilst incurring the minimum of hindrance to the users' normal tasks.
Acknowledgements

Thanks and credit are due to my principle supervisors Professor Robert Brown and Dr. David Wright for their guidance throughout this study. Thanks are also due to Dr. Ivan Jordanov and Dr. Zahari Taha for their valuable advice.

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Thanks are offered to the volunteers who participated in the trials, especially Tim Plunkett, who offered his invaluable time and expert opinion. I would also like to thank the many people involved in RP, both commercial and research based, who freely offered their honest information and opinion, greatly contributing to this study.

Thanks also to Tracey Davies and Anna Filson for their editing of this thesis. Finally, I offer my thanks to all of the staff at the DERC past and present who have all in some way supported me and contributed to this research.

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Cardiff
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<td><strong>EOS GmbH</strong></td>
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EOSINT: EOS trade name for their selective laser sintering machines.

FDM: Fused Deposition Modelling - a free form build technology that creates articles from extruded molten plastics.

Helisys Inc.: USA based company producing laminated object manufacture machines.

Kira: Japanese manufacturer of laminated object manufacture machines.

LOM: Laminated Object Manufacture - a free form build technology that creates articles from layers of profile cut paper.

LOM 1015: Helisys trade name for their smaller laminated object manufacture machine.

LOM 2030: Helisys trade name for their larger LOM machine.

Meiko: Japanese manufacturer of stereolithography machines.

Mitsui Zosen: Japanese manufacturer of stereolithography machine.

MJM: Multi Jet Modelling.


N2: Nitrogen gas.

Photopolymerizable: A liquid or resin that will solidify (cure) when exposed to certain wavelengths of light.

QuickCast: 3D Systems trade name for their hollow build style for sacrificial investment casting patterns.

Reverse Engineering: To create computer model of an object, by digitizing or scanning.

RP: Rapid Prototyping - general term for free form build technologies.

RPT: Rapid Prototyping Technologies (or Techniques).

RP&M: Rapid Prototyping and Manufacturing.

RP&T: Rapid Prototyping and Tooling.

SGC: Solid Ground Curing - a free form build technology that creates articles from photopolymerizable resin in layers using profile stencils.
<table>
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<th>Term</th>
<th>Description</th>
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<td>Sintering</td>
<td>Fusing to solid from a powder, usually by heat.</td>
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<td>Sinterstation 2000</td>
<td>DTM trade name for their smaller SLS machine.</td>
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<td>Sinterstation 2500</td>
<td>DTM trade name for their larger SLS machine.</td>
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<tr>
<td>Skin &amp; Core</td>
<td>EOS trade name for their hollow build style for sacrificial investment casting patterns.</td>
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<td>SLA</td>
<td>Stereo Lithography Apparatus - a free form build technology that creates articles from photopolymerizable resin using a laser.</td>
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<td>SLA-190</td>
<td>3D Systems trade name for their smallest SLA machine.</td>
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<td>SLA-250</td>
<td>3D Systems trade name for their smaller SLA machine.</td>
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<td>SLA-350(0)</td>
<td>3D Systems trade name for their mid range SLA machine.</td>
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<td>SLA-500(0)</td>
<td>3D Systems trade name for their largest SLA machine.</td>
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<td>SLS</td>
<td>Selective Laser Sintering - a free form build technology that creates articles from heat fusible powder using a laser.</td>
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<td>STEREOS</td>
<td>EOS trade name for their stereolithography machines.</td>
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<tr>
<td>STL</td>
<td>Stereo Lithography - computer file format used by most free form build technologies.</td>
</tr>
<tr>
<td>TCT</td>
<td>Time Compression Techniques (Technologies).</td>
</tr>
<tr>
<td>Teijin Seiki</td>
<td>Japanese manufacturer of stereolithography machines. Under licence from DuPont.</td>
</tr>
<tr>
<td>TPM</td>
<td>TriPropylene glycol Monomethylether the solvent used for cleaning uncured resin from stereolithography parts.</td>
</tr>
<tr>
<td>Ushio</td>
<td>Japanese manufacturer of stereolithography machines.</td>
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<td>UV</td>
<td>Ultra Violet Light.</td>
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<tr>
<td>Vacuum Casting</td>
<td>A method of producing small production runs of plastic parts by making a silicone mould from a master pattern or prototype.</td>
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<td>VR</td>
<td>Virtual Reality.</td>
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1.1 Introduction

This study addresses the need to tackle a lack of design and development knowledge often occurring in small companies. Although small companies can have inherent advantages in terms of versatility and adaptability they are frequently disadvantaged by a lack of resources, both financial and manpower, compared to large corporations. There is a noticeable lack of knowledge in the area of new technology in many small companies which may reduce their competitiveness against larger competitors who are able to exploit new techniques and processes. One particular area of design technology knowledge often lacking in small companies is rapid prototyping and tooling. These are a group of high technology processes which allow the rapid generation of accurate prototypes directly from computer aided design (CAD) data. As more small companies invest in three dimensional CAD the ability to exploit these technologies increases, however a lack of knowledge often means the potential benefits are not realised.

To address this issue a method should be devised of taking expert knowledge relating to rapid prototyping and supplying it in a quick and convenient manner to designers in small companies. Access to this expert knowledge should help redress the balance in design technology between small companies and large corporations. To accomplish the aims of this research will require the following programme of work:

1. Ascertain the nature of the available input data (from the user) to the system and the desired output (to the user).

2. A thorough review of current rapid prototyping (RP) technologies; assessing their availability, capabilities, applications, advantages and problems. This review should also include complementary processes which are applied in combination or facilitated by rapid prototyping. The review should reflect current practice in UK industry as opposed to theoretical specifications.
3. Investigate previous attempts at similar systems. From the information collected in the review, criteria and structure should be identified which will allow the selection of appropriate rapid prototyping routes.

4. Investigation of potential approaches to development of the system. Quantifying and classifying important procedures, parameters and properties.

5. System development including the creation of the graphical user interface, program structure selection rules and estimation calculations.

6. System trials with target users and RP experts.

7. Response to the trial findings.

8. Evaluation of the system with reference to the original aims.
1.2 Background

In manufacturing today competition, especially in established markets, can be fierce. With many companies fighting for market share with similar core technologies greater emphasis has been placed on product differentiation and brand identity. This has initiated a trend amongst manufacturers towards more fashion led, innovative products and targeted niche markets. This results in shorter product life cycles and therefore smaller production volumes of a given design. For companies to be able to fully exploit such rapidly changing fashions and trends products have to be brought to the market in increasingly short timescales. Research has shown that time to market can be the single most important factor affecting a company’s profitability. Figure 1.2.1 shows comparative effects on profits of product development problems [1].

As the graph in Figure 1.2.2 shows, the vast majority of the cost of introducing a new product is committed in the design phase, it is therefore crucial that the design phase is completed not only quickly but also thoroughly and with careful
consideration of the implications for tooling and production. Mistakes made at the design stage can lead to alterations being made at the tooling or production stages which could lead to massive costs with potentially disastrous effects on profits. Therefore, there is increasing pressure on product development teams to drastically reduce time to markets whilst at the same time predicting and controlling the committed costs. This involves the need to be “right first time” with the design and tooling of a new product.

There have been many studies into the optimisation and acceleration of product development in large companies. Many of these have concentrated on managerial and procedural issues which can be a major factor in large companies. Others have investigated the use of design tools and aids which speed up design and development. Large companies often have the resources available to investigate or create and implement technological design aids and tools. However these strategies are applicable to the many small manufacturing companies operating in the UK.

In 1990, a survey showed that 95% of the three million businesses in Britain
employed a staff body of less than 20 [2]. Within Wales (the local environment of this study) two thirds of companies employ fewer than ten people [3]. Such a contribution is inevitably critical to the success of the UK economy and so the factors affecting the performance of SMEs have become a matter of no small interest. Sentence and Clarke report that in Britain, an increase of one-third of in-house design is directly associated to a rise in growth-rate of manufacturing output by 0.3% a year [4]. Effective use of design and product development has been identified as an area of major importance in increasing the success of small companies in the manufacturing sector [5]. From these figures alone, we can see the profound effect that effective product design and development has on commercial and economic success of both SMEs and the economy as a whole.

One of the intrinsic advantages of the small to medium sized manufacturer (SME) is speed and versatility. Management is often minimal and focused and facilities more versatile. Consequently SMEs often have the ability to implement change much faster than large companies. With the trend towards niche markets and shorter product life cycles with their smaller production volumes, the SME can compete on better terms with large manufacturers. However, due to the comparative lack of resources, problems are encountered by SMEs when trying to utilise high technology. Therefore, there is considerable scope to improve the transfer of technology and knowledge to SMEs. The competitiveness of an SME can be enhanced if they are able to exploit the latest design and manufacturing technology whilst maintaining their rapid decision making, short product development times and manufacturing flexibility.

The competitiveness of SMEs is crucial to the economic success of the UK and in particular to regions where major primary industries are in decline. For example, since the cessation of mining in South Wales the vast majority of companies are SMEs. Consequently their success and growth is crucial to the economic survival and regeneration of the region.
With these considerations in mind there has been increased interest in improving the competitiveness of SMEs both in the UK and across Europe. Much work is being done to enhance the technology and knowledge within SMEs. This study investigates the creation and viability of a design advice system which will enable SMEs rapid, convenient and affordable access to expert knowledge in a particular field, in this case rapid prototyping.
1.3 Identification of User Need

1.3.1 Access to Rapid Prototyping Services and Information

During the early development of Rapid Prototyping (RP), large companies such as those in the aerospace and automotive sectors championed the new technology; buying in the processes and training their staff to exploit the new medium. This was most typical in the USA, where rapid prototyping was largely pioneered. In Britain, those companies with American affiliations were the first to accept and implement Rapid Prototyping and many UK universities showed an interest in the integration of RP in industry. Much of the early academic-based research was designed to increase the accuracy and reliability of the processes. These projects often involved major European companies, which, although doing much to pioneer RP, did little to help the many small manufacturing companies in the UK.

In contrast to large manufacturing companies, small enterprises find it difficult to justify the risk of buying into unproven technologies. As the RP industry has matured and processes have become more accomplished, the risks have decreased and many smaller companies have begun to invest in RP. For very small manufacturing companies, access to Rapid Prototyping information is limited and resources are even less prevalent. For these companies, the implementation of RP techniques may prove somewhat over-speculative since they are handicapped not only with a lack of human, but also financial resources, making training and keeping pace of development an immoderate expense.

Most companies in the UK learn about Rapid Prototyping from service providers at trade shows and through advertising. For many, the main method of information dissemination is directly from this source and that information may or may not be biased, depending on the service provider in question. Small companies will almost certainly not have the capital to invest directly in the technology and are therefore reliant upon service bureaux, who offer the most economical alternative. At present, there are very few independent consultants working in Rapid Prototyping in a
purely advisory role and indeed, even if these were more prevalent, the costs incurred in hiring an RP consultant may well exceed that of the prototyping itself. Moreover, small companies are often unaware of how and when to access design advice and even when this advice is offered, SMEs can prove reluctant to activate a change in their established practices. To compound matters, opinion exists which suggests that external design consultants sometimes fail to effectively consider the problems of the small business and so their services can prove disturbingly ineffective [6].

Some small companies get involved with Rapid Prototyping through academic institutions with RP facilities. This involvement might take the form of training courses, seminars or clubs and may or may not be limited to the equipment in the establishment’s possession. Additional problems arise through geographical restrictions. Many small manufacturing companies are based outside major industrial conurbations, where the majority of UK Rapid Prototyping establishments are positioned. Areas where this is a particular problem include Scotland, Wales and the South West of England. For individuals in these areas, access to academic establishments or other RP service providers may prove too time consuming and costly to consider. With these complications and the additional problems encountered by the small company, it becomes imperative to look to a system which can provide accurate RP information in a fast and convenient manner [7].

As described earlier, small companies may not have the resources available to devote time and manpower to exploring new and untried prototyping methods and as such may be reluctant to change from established processes which they know will give satisfactory results. In some cases, although prototyping lead times can be much shorter when using rapid prototyping techniques, a lack of knowledge, especially in SMEs, can lead to delays during which different possibilities are investigated. These delays may lead to a situation where the overall lead time approaches, or even exceeds that of established techniques, as illustrated in Figure 1.3.1.1.
Alternatively companies lacking full and detailed knowledge may mistakenly implement totally inappropriate processes.

Some companies have been so enthusiastic about the sexiness of TCT, or RP, or SLA, and determined to use them that they have used the wrong processes for their project. [8].

In either of these circumstances small companies are not able to fully exploit the potential benefits of current product development technology.

![Diagram](image)

Figure 1.3.1.1. Prototyping lead time comparison.

This study explores a range of possibilities which might help designers and those involved in product development to plan and select the optimum process for prototyping. This system should aim to help small companies to maintain or enhance their competitive advantage; allowing the successful exploitation of modern prototyping technologies and so enabling SMEs to save time and cost during the product development cycle.
1.3.2 Potential Prototyping Problems

Whichever model of the design process is referred to, there will always come a point at which the design has to face evaluation in a physical form. If the design process is shown in its simplest form, as in Figure 1.3.2.1., it can be seen that at any point from concept design through detail design there may be a need to physically evaluate the aspects of the design. The production of prototypes allows characteristics and functions of the design to be tested before it is finalised and series production can begin. These tests can vary widely in their demands according to the product type, legislation and standards, or the stage of development at which they are used [9]. For example, at an early stage in the development a model may be made to assess the visual appearance of a design followed at a later stage by prototypes made from the production materials used for reliability tests.
The selection of appropriate manufacturing processes has long been acknowledged as of paramount importance when embarking upon the development of a new product [10]. In parallel to this the selection of the most appropriate prototyping methods can be seen as a similar problem contained within the design phase. The prototype testing phase of product development can be crucial to the success or failure of a new product. A product that is not fully tested may fail in use, with potentially disastrous effects on sales. A poorly planned prototyping phase could lead to unacceptable delays in getting the product to market. In addition to these considerations the market for many products is changing. There is a noticeable trend towards shorter product lifespans, more design variation, and a greater demand for niche products with smaller production volumes. All of which puts increasing pressure on companies to drastically reduce product development timescales without compromising the overall quality of the product.

To meet these aims it is important for companies to take full advantage of technological advances at every stage of product development. A key problem now facing designers is choosing the optimum prototyping route for a given product. The advent of Rapid Prototyping and Tooling (RP&T) has opened up a whole raft of new possibilities for manufacturing physical prototypes in addition to the many traditional methods already used.

These new prototyping processes, described in Chapter 2, include; Stereolithography, Laminated Object Manufacture, Fused Deposition Modelling and Selective Laser Sintering. These technologies work in essentially the same way; by taking three dimensional CAD data and slicing it into layers. The machines then build the models in a layered manner. The machines are automated and produce accurate three dimensional models of the CAD object. The ability to produce these accurate models quickly and cheaply has enabled the use of various subsequent tooling processes which use the RP model as a master pattern. Of course all of these processes have characteristic advantages and limitations and the designer has to take these into
consideration before deciding which route to choose.

With so many different possible routes available, combined with the rapid development in this field, it is difficult for the designer to stay abreast of the latest improvements. The processes also vary greatly in their capabilities and some of the issues concerning their applicability for a given design can be complex. Estimating costs and lead times is also a complex issue. It would be unrealistic to expect the designer to become an expert in all of the possible processes especially in the small companies that this study is aimed at.
1.4 Identification of Problem to be Addressed

Hypothesis

To establish whether it is feasible and practical to create an automated design advice system which is capable of successfully guiding small companies through the selection and implementation of rapid prototyping and tooling technologies. The system should provide advice similar in content and delivery to that provided by an expert person.

1.4.1 Potential Solution

Due to the issues described previously an opportunity exists to produce a ‘design advice system’ which can aid the designer to plan and account for the prototyping stage of their design project at the earliest possible time. Such a system should take full advantage of information available from Computer Aided Design (CAD) and remove the burden of research, knowledge and calculation from the designer.

The aim is to allow small companies to successfully exploit the speed of rapid prototyping by eliminating the need to devote valuable time and manpower to researching and evaluating new techniques. This time saving is illustrated in Figure 1.4.1.1 (incorporating the routes shown in Figure 1.3.1.1. for comparison).
A decision was taken to target the RP selection system towards a particular user. The targeted user would be the designer, project manager or whoever is responsible for planning the prototyping stage of product development. The system is aimed specifically towards these users within small companies. As has been mentioned above, large companies usually have the resources available to have a person trained in specific skills, but small companies do not. The system should guide, aid, recommend, warn, and educate the user. Such a system would have to be very quick and simple to use. It should require the minimum effort on the part of the user and provide as much information as possible.

If we assume that this system should be used for planning the prototyping stage then the earlier it can be used the better. Many things about the part to be prototyped
will not be specified yet and the design won’t be finalised. The system should be able to operate with this limited information to provide an initial suggestion. As the design progresses more information will be available and the system can be used again to provide a more detailed solution. Design is an iterative process and the system should be conducive to use within this iterative process. The designer may not know specific mechanical properties of the materials he may specify for the product.

There is little point attempting to produce highly accurate figures for cost and lead time as this will depend on the eventual service provider. Several estimates from different service providers will be similar but will vary by some degree. The system should furnish the user with enough information with which to ask for and specify an estimate from an RP service provider. It should also provide enough guidance for them to understand the service providers response. It is conceivable that a directory of service providers could be incorporated into the system.

1.4.2 Core Rules and Restrictions

In order to create a rapid prototyping selection system it is necessary to classify the information used. If these inputs are prioritised the system can work through the process of selecting methods according to the most important factors. Some of the information will come from the object description. Of the remaining information required one of the most important factors in the case of prototyping will be the number of parts required. This is simple to specify as it is a numerical integer value, and can be inputted by the user.

Other things the user will have to specify include characteristics of the component which cannot be automatically derived from the object description and the physical properties required of the prototype part. These will depend on the purpose for which the prototype is being made.
1.4.3 Process Restrictions

For every rapid prototyping and tooling method there are limiting factors. These could be, for example, minimum draught angles or overall size limits. The system should take these into account and reject processes which cannot meet the criteria specified by the user.

Inputs which fall outside the capabilities of the processes available should be rejected. This should be indicated to the user with an explanation of which input cannot be satisfied, along with either a suitable default value or the upper and lower limits of the value.

1.4.4 Functional Limits

For the purposes of the study, the system will have to be limited in functionality. After some deliberation it was decided that the system should focus the prototyping of injection moulded plastic components as this process is in widespread use and the tooling costs associated with it are high. There is, therefore, greater opportunity to save time and money. This is also the area where the most work has been carried out in rapid tooling development.

Rapid prototyping and tooling processes which are not fully established in the UK, which would be difficult to validate, or for which there is insufficient information, will also be omitted.

1.4.5 Conclusion

A potentially successful method of creating an aid to the planning of the prototyping stage of product development would be the creation of a computer based selection system.

Process knowledge could be stored by the system allowing users to gain a recommended prototyping route from information supplied by them. Such a system
could take advantage of information, concerning the components to be prototyped, contained in Computer Aided Design models.

There are many ways such a system could be constructed, using different software solutions. The methods chosen should allow a user friendly interface, providing as much information to users as they require. The system should also require minimal user input. The approach chosen may incur some disadvantages but should be the one best suited to answering the needs of the study within the limits stated.
1.5 Information Available from the User

The information available consists of the designer’s demands and what they know about the product before or as the prototyping stage is undertaken. This information will form the input into the decision aiding system. The selection criteria arrived at is similar to those laid out by S. O’Reilly and K. Denton [11]. The criteria they noted were;

1) Number of parts required.
2) Schedule.
3) Should the part be in a material that is of production quality or only similar?
4) The route should fall within budget requirements.

For the purposes of this system however it was decided that setting a budget and schedule should not be part of the initial user inputs as this may require some prior knowledge of rapid prototyping, although it may be desirable to input ‘ceiling’ values for cost and timescale. In the simplest terms the information available can be summed up as;

a) Object description.
b) Number of prototypes required.
c) Intended prototype use.
d) Other considerations.

a) Object Description

The system will require certain key characteristics of the component to be prototyped. These are the characteristics that will determine which processes are suitable for producing the object accurately. These characteristics can be obtained or derived from a description of the object in question. For example, these may include the overall size, wall thicknesses and features of the object. In addition other properties, such as the intended production material, may be specified.
b) Number of Prototypes Required

The user will need to specify how many prototype components are required. This is simply an integer number, which in prototyping terms could mean anything from one to many thousands. The number of prototypes required will have an important effect on the methods used to produce them.

c) Intended Prototype Use

The prototype or prototypes in question will be made for some form of evaluation or testing. Depending on the nature of these tests they will place certain physical demands on the prototype. The designer will need to specify these demands.

d) Other Considerations

The system should guard against the input of erroneous data. Warnings should be given before trying to arrive at a solution to eliminate the possibility of misleading results. Suggestions of more suitable values or limits should be given along with the warnings to guide the user towards valid values. Reasonable default values should be made available where inputs are not yet known. Also, as mentioned above, limits for cost and timescale could be incorporated.
1.6 Information Required by the User

The information required, i.e. the output of the system, should help the user to plan the prototyping stage of the development of the product in question. The information should be presented in a format that is readily understandable to the user and appropriate to the planning process. The system should furnish the user with enough information to seek a detailed estimate from a service provider. In the simplest terms the information required can be summarised as:

a) The methods to be used.
b) Estimated cost.
c) Estimated lead time.
d) Other considerations.

a) The Methods to be Used

The designer will need to be shown the suggested prototyping route based upon their criteria. Where the route consists of multiple processes or steps this should include all of the individual methods involved in the route. The information given should also describe the processes and any additional actions required to complete the suggested route.

b) Estimated Cost

The output should indicate likely expenditure for the suggested route. All aspects should be allowed for. Where multiple processes are used the costs for each process should be indicated to allow the designer to understand the proportion of the cost attributable to each process.

c) Estimated Lead Time

The output should indicate the lead time necessary for the suggested route, in terms of working days. Again, where multiple processes are used the lead time for each process should be indicated.
d) Other Considerations

If there is no route which satisfies all the criteria, the best compromise solution should be suggested. The criteria which could not be satisfied should be indicated and alternative values or limits suggested.
1.7 References


2.1 Rapid Prototyping Technology

2.1.1 Introduction to Rapid Prototyping & Tooling

This text intends to be a review of Rapid Prototyping and Tooling (RP&T) technologies as they stand today. A brief history of Rapid Prototyping techniques will be followed by a description of the different types of system that are currently in use. Some of the applications to which these technologies have been successfully applied will also be described. The benefits of using RP will be discussed along with improvements or changes that can be applied to the systems and applications to lead to greater or more efficient use of the available technologies.

There follows a review of the use of current Rapid Tooling (RT) methods. Rapid Tooling processes that are currently in use will be described including some of the areas that they have been applied to. Then some of the potential advantages and problems associated with the application of Rapid Tooling will be noted. Finally a view on future development will be given.
2.1.2 A Brief History of RP

Rapid Prototyping (RP) is a generic phrase coined to cover a relatively new set of manufacturing technologies which enable the generation of models without tooling or manual work. In the late 1970’s and early 1980’s several people were working on RP systems, these included A. Herbert at 3M, H. Kodama at Nagoya Prefecture Research Institute, and C. Hull at Ultra Violet Products. They were all working independently on systems utilising Ultra Violet curing resins built up in layers. Kodama and Herbert stopped working when funding was no longer available. Hull, with support from Ultra Violet Products, continued and gained a patent in 1986, for which he coined the phrase Stereolithography (“three dimensional printing”). Hull and R. Freed formed 3D Systems with backing from the stockholders of Ultra Violet Products. 3D Systems launched the first commercial RP system called the SLA-1, in November 1987 (Stereolithography Apparatus). 3D Systems also created the STL (Stereolithicry) file format, which describes three dimensional surfaces as faceted triangles. All of the current RP technologies now use the STL file as input data. In 1988 they formed a partnership with Ciba-Geigy who would develop resins specifically for the RP system. In 1989 the SLA-1 was upgraded and called the SLA-250, this is now the most popular RP machine in the global market [1].

Following the establishment of 3D Systems, other techniques were researched and some developed into commercially available machines. In Japan stereolithography was copied by several manufacturers, but these machines are not yet available outside Japan. Most of the competing systems were developed in the USA, with the notable exception of Cubital’s Solider system which was developed in Israel. Stereolithography and selective laser sintering systems were also developed by Electro Optical Systems (EOS) in Germany. One of the more successful systems was developed by Helisys in California, their Laminated Object Manufacture (LOM) machines are now one of the most common types of RP machine. As SLA and LOM became established in the market place both companies developed larger machines with build volumes twice the size of the original machines.
The large car and aerospace companies were among the first to embrace the new technologies followed by a number of companies offering bureau services to industry. Cheaper machines were also developed such as the Fused Deposition Modelling (FDM) process from Stratasys. Recently there has been increased development of smaller cheaper machines utilising jetting print head technology, such as the Actua developed by 3D Systems and the Model Maker Machines developed by Sanders Prototype.

2.1.3 Common Ground

2.1.3.1 Input Data Format

All current RP systems require information from three dimensional Computer Aided Design (CAD) data. The CAD model must be a solid or fully trimmed surface and is usually translated into a StereoLithography (STL) file. Generally speaking it is better to start from a solid model rather than a surface model as any gaps between surfaces will cause problems during building. The STL file was developed by 3D Systems and has since become a de-facto standard. All current RP systems can use the STL file format as input data. STL files are triangular faceted models derived from the CAD solid model.

All RP systems work in essentially the same way, by taking the STL file and slicing it into a number of very thin layers. The data for each layer is then 2D control data for whichever process is used to create the layers. The thickness of each layer is determined by the process and material being used.

This simple geometry of the STL file format allows the angle of faces to be identified. This is required for the generation of the support structures necessary for stereolithography. The support generation software identifies facets at angles less than some preset angle to the build plane, effectively down facing or overhanging surfaces, and connects supports from the build platform to these facets. This way the model is
supported away from the build platform by a thin structure which can be broken through easily to remove the part from the platform without damage. The ability to identify facets with certain angles also allows upward and downward facing surfaces to be built in specific build styles to improve surface quality or add features such as vent and drain holes in hollow parts.

The STL files are produced by the CAD system via an additional translator. Most 3D CAD systems are able to produce STL files. The STL file is then passed in either binary or text (ASCII) format to the preparation computer of the RP machine. STL files can be large, especially in text format, and transfer is usually by: Digital Audio Tape (DAT), Quarter Inch Tape (QIT), or increasingly often, FTP, ISDN and Email.

The STL file format is not ideal as the faceted model can only approximate the CAD model. The resolution of the STL file to the CAD model is determined by specifying a maximum deviation, which basically determines the minimum size of the triangular facets. The STL file format is described in greater detail in Chapter 5.4: The STL File Format. The STL file is also not ideal for RP systems which do not require the generation of supports. There has been research into alternative data formats that slice the CAD model directly. This however makes support generation for SLA very difficult. This approach was necessary for the building of medical models from scan data which is made up of a series of contours and has been successfully used with special support generation software. The application of improved data formats will depend on closer co-operation between CAD vendors and RP system manufacturers. It is likely that future CAD data standards, such as STEP, will address issues relating to RP compatibility.

2.1.3.2 Support Structures

Another common point is that all RP systems require some form of support for the part being built. This may be built along with the model, unused material surrounding the model or a separate material added around the model. This in turn
leads to some degree of material waste. Control files have to be generated for support structures that are built along with the part and their building adds to the overall build time. Secondary material support structures add another process step and add to build time and possibly require some processing time. Support provided by unused build material requires no file generation or additional process steps. All techniques require some process or labour to remove these support structures and clean up the parts.

Finally, due to the layered method of building these parts they all display a “stair stepping” effect and therefore require some degree of hand finishing. All of the current processes require some degree of operator training and experience to be used successfully. The processes differ in how they produce the layers and in what material.

2.1.3.3 Comparison with Computer Aided Machining

There are many situations where RP techniques can prove advantageous compared with Computer Aided Manufacture (CAM). The basic premise of building with a material to create a parts means that less material is wasted. RP techniques produce the part in one operation whereas even 3 or 5 axis machining requires successive operations, most obviously one for each side of an object and any undercuts. RP techniques are not complexity dependent, whereas increasing complexity has a direct effect on the number of operations required for machining. Features which prove difficult with machining are easily constructed with RP systems, for example draught angles and internal square corners.

Another key advantage is in the production of small, thin walled or shelled items where suitable clamping would be difficult. Surface finish with CAM can be very good but this depends on the number of passes which are made with increasingly small cutters increasing process time.

A disadvantage of RP techniques when compared to machining is the stepped
effect caused by the discrete layer thickness. However, this may be considered as a similar finishing problem to the tool paths which remain on machined parts. Perhaps the most significant disadvantage of RP techniques is the limited range of materials available. Although the range of materials is increasing and their properties are being improved they are still driven by RP processing requirements whereas many materials can be machined by altering the cutting parameters. When considering the prototyping of plastic components neither Rapid Prototyped or machined parts will display the same physical characteristics as moulded ones, even if the same material is used. This is due to mould flow characteristics which may alter the physical properties of the material as it is formed in the mould.
2.1.4 System Type Break Down

The simplest way of grouping system types is initially by the type of build material they use, then sub-grouping according to the layer construction process, and finally sub-dividing again by manufacturer. See Table 2.1.4.1. There are six basic process types of RP process:- stereolithography, solid ground curing, laminated object manufacture, fused deposition modelling, selective laser sintering and jetting head technology.

![Table 2.1.4.1. RP System type breakdown according to material.](image-url)
2.1.4.1 Stereolithography (SLA)

Principle

Liquid resin is cured to solid by Ultra Violet (UV) light accurately positioned by a laser. The laser scans the layers onto a platform. Successive layers are cured by lowering the build platform and applying an exact thickness of liquid resin.

Detail

The process was originally developed by 3D Systems Inc. and operated as follows. Parts are made by curing a light sensitive liquid resin to solid using an Ultra Violet laser. Parts are built onto a platform which lowers by a layer thickness after each layer is produced. There are wait states which allow the liquid to flood over the part and level out. These wait states will depend on the viscosity of the resin. Then a recoater blade will pass over the liquid levelling the resin and removing any bubbles or debris from the resin surface. However, this method means that there are problems with building objects with trapped volumes as the liquid in these areas is not in communication with the resin in the vat and does not level out. See Figure 2.1.4.1.1. This recoating method has recently been replaced with an improved system which will feature on machines built from now on. With the new system a U-section vacuum recoater blade moves over the vat picking up a small amount of resin and depositing it over the part. This means the part is lowered by only a layer thickness and the recoating is done in one pass of the blade. This reduces the wait states and the problems associated with trapped volumes. This method also allows thinner layers to be produced. See Figure 2.1.4.1.2 [2, 3].

The EOS STEREOS machines differ here slightly in that the layers of resin are deposited over the part by a moving blade through a precise slot, hence the trapped volumes present less of a problem. The EOS system however is more likely to require maintenance to the recoater mechanism. See Figure 2.1.4.1.3 [3, 4].
The speed of the machine depends on how much energy the resin requires to polymerise, as the power of the laser is constant if more energy is required the laser must travel slower. Material properties and part accuracy also depend on the resin characteristics. As the material polymerises there will be some degree of shrinkage, this can be accounted for in the build parameters, but may also lead to other problems most notably curl. This was especially true early in the development of SLA when most systems used Acrylate based resins. These problems were partially eliminated by altering the build style, i.e. the way the laser scans the layers. The development of epoxy resins eliminated these problems as it shows very low shrinkage. This results in very accurate parts although more energy is required to polymerise the material and therefore build times are longer.

Solid resin parts proved unusable as sacrificial investment casting patterns due to the fact that the material expands with heat cracking the ceramic shell. To enable investment casting quasi-hollow build styles were developed. These produce parts as a skin, with a supporting structure inside, and so upon burn out they collapse in on themselves. The uncured resin is drained and centrifuged out using vent and drain holes which are then plugged with wax. The surface area of this type of part is very large and parts will absorb moisture readily so they must be used quickly and stored in dry conditions [2, 30, 31, 45].

Advantages are :-
- Well developed, reliable machines and software.
- Well established sales, support and training.
- High accuracy, good surface finish
- Little material waste
- Low maintenance

Disadvantages :-
- High cost of machine and materials
- Resin handling requirements
- Trapped volumes difficult (for current machines)
The laser draws first layer.

Table drops below surface of resin.

The recoater blade levels out the resin surface.

Table exactly one layer thickness below resin level. The next layer can now be drawn.

Figure 2.1.4.1.1.
3D Systems old recoat method.

The laser draws first layer.

Table drops exactly one layer thickness below surface of resin. Recoater passes over depositing precise layer of resin.

Table drops exactly one layer thickness below surface of resin. The next layer can now be drawn.

Figure 2.1.4.1.2.
3D Systems new 'Zephyr' recoater.

The laser draws first layer.

An exact layer thickness of resin is deposited by a recoating blade.

The next layer can now be drawn.

Figure 2.1.4.1.3.
EOS recoat method.

Figure 2.1.4.1.4.
2.1.4.2 Solid Ground Curing (SGC)

Principle

Liquid resin is cured to solid by Ultra Violet (UV) light exposed through an optical mask. A new mask is made for each layer. Uncured resin is removed and replaced with molten wax which is chilled to solid to provide support. The layer is then machined flat to the exact layer thickness required. The build platform is then lowered and fresh resin applied. See Figure 2.1.4.2.1.

Detail

Parts are made by curing UV light sensitive liquid resins to solid using a UV lamp and optical masks. The masks are produced on a glass plate using the same technology as photocopiers. The build sequence involves several steps, first a layer of photopolymer is deposited and the first optical mask is produced and positioned above the resin, the resin is then exposed by a UV flash lamp. The mask is removed and prepared for the next layer, uncured resin is vacuumed up and the resin receives a second UV flash. Then molten wax is deposited around the cured resin and solidified by a chilled plate. The whole area is then machined level to the layer thickness required, a second vacuum removes the chippings. The build table lowers and fresh resin is deposited, and so on. When the part is complete the wax is melted away revealing the parts, no post curing is required. This process eliminates expensive lasers but means the machine is very complex and large (6 by 13.5 feet) weighing many tons. It is also extremely noisy due to the vacuum operations. These limitations make it suitable for installation in factory environments only. The machine also requires a considerable amount of operator attendance in comparison with other RP machines [7, 8, 9].

The process does not require support structures as this is provided by the wax. Therefore the whole build volume can be utilised by nesting parts in any orientation anywhere in the build volume. However, the whole area has to be built, so the available area should be filled with parts for economic building. Build time is
dependent only on height as the time to produce one layer is fixed regardless of geometry. Also the uncured resin cannot be reused because the optical mask allows a certain amount of UV through and the resin is degraded, therefore material waste is very high. The degraded resin is bought back by Cubital. Consequently purchase of an SGC machine would only make economic sense when a large throughput of models were required [38].

Surface finish and accuracy are not as good as may be expected due to two main causes. The first being incomplete removal of uncured resin. A small amount of resin remains in the corner between the new cured layer and the previous layer, this gets cured in place by the second UV flash. See Figure 2.1.4.2.2. The second cause of poor surface finish and accuracy is the fact that the optical masks are produced as a raster scan, like laser printers, and the resolution is poor at 300 lines per inch (lpi) this gives a stepped effect on edges not parallel to the scan line. This may be improved by a move to 600 lpi resolution in line with current laser printer specification. A resolution of 1000 lpi would be sufficient to eliminate the effect [10].

Advantages :-  No supports to prepare, build or remove
                No post curing required

Disadvantages :- Very large and noisy machine
                 Very high material waste
                 Poor accuracy and surface finish
                 Resin handling problems
Figure 2.1.4.2.1. Solid Ground Curing.

Figure 2.1.4.2.2. Problems associated with SGC.

Figure 2.1.4.2.3. Cubital Solider 5600.
2.1.4.3 Laminated Object Manufacture (LOM)

Principle

Inert flat sheet materials are cut to the profile of a layer. Fresh material is bonded onto the previous layer and the next profile is cut. The layer thickness is dependent upon the thickness of the sheet material.

Detail

With the more common Helisys machines parts are made by cutting layers of paper with a CO₂ laser using an x-y plotter mechanism. See Figure 2.1.4.3.1. Build time is relatively quick as only the perimeter of the layers is drawn. Builds can be speeded up by cutting more than one layer of paper at a time. The paper is either 0.1 mm or 0.2 mm thick (nominally). The paper is adhesive backed and the layers are adhered by a heated roller. The paper is fed from a roll and passes over the build table, unused paper is taken up by another roll. The laser cuts a support wall enclosing the part. Material which is outside the part and inside the support wall is cut into squares. The build table lowers and fresh paper is fed over. When the part is complete the block is removed from the table and the support wall is removed. The waste material is broken away to reveal the part [11, 12].

To obtain a cut that penetrates only one layer of paper requires the speed of travel and laser power to be adjusted by the operator. Good bonding between layers depends on the compression, temperature and speed of travel of the heated roller, which is again adjusted manually until it is satisfactory. These settings require periodic checking and generally the machine needs regular maintenance. Extraction of the smoke produced creates a tolerable amount of noise. Although there is a certain amount of waste material, the paper is relatively cheap. The low cost of the raw material combined with the fact that the laser only scans the perimeter makes LOM particularly suitable for very thick sectioned parts. Thin walls can be produced on LOM machines but prove to be rather weak and may be damaged when the waste material is broken away [14, 38].
The Kira system is similar except that standard A3 copy paper is fed in sheet form by a photocopier mechanism. The adhesive is applied as toner would be. A hot plate adheres the layers and cutting is by carbide knife using an x-y plotter mechanism. There may be advantages to this approach compared to the Helisys method. Most notably less lateral stress is induced on bonding because the hot plate presses evenly downwards as opposed to a roller which imparts a lateral force as it travels across the part. There is also the cost advantage of standard (photocopier) components and the elimination of lasers. Breaking out parts is also easier as the adhesive is only applied to the cross sectional area of the model. The paper area outside the model boundary only has a small amount of adhesive applied in a grid pattern [6].

The Sparx Hot Plot machine cuts relatively thick (nominally 1 mm) layers of expanded polystyrene. The material is cut by an electrode using an x-y translation stage. The layers have registratin holes cut which locate on pins when the layers are assembled by hand. The material has a self adhesive backing. This makes it only suitable for large parts with little complexity, however the machine is considerably cheaper than other LOM machines [13].

Another simple and inexpensive system, called JP System 5, has been developed by Schroff. The software slices STL or CAD files which control ‘off the shelf’ computer controlled vinyl cutters to produce the layers from label paper nominally 0.21 mm thick. The layers are then assembled manually on a registration board. Model sizes possible depend on which vinyl cutter is specified, ranging from 300 mm square (from Roland) to 900 by 1200 mm (from Graphtec).

The costs are therefore comparatively low. The software costing around £6000 and the vinyl cutters ranging from £1,895 to £11,595, when the costs of materials, warranties, training and computer hardware are added a system can be set up for as little as £14,000 with taxes in the UK making it the cheapest RP system available [39].
LOM materials undergo no state change and therefore shrinkage is not a problem. Although the height may alter slightly as built-in stresses are relieved. Paper parts produced are good for handling and feel similar to wood. Finished parts will however, absorb moisture readily and must be sealed to prevent distortion due to this. The parts will burn out of investment casting shells with no problems except for a little ash which needs to be cleaned out. Solid LOM parts have very good compression strength and can be used as tools for vacuum forming or light duty press work [15, 16, 46].

An inherent problem when breaking parts out is that areas of the part which face upwards or downwards are bonded to the waste material. In practice this is only a problem where the distance between laser cuts is more than around 10 mm. This is partly combated by a finer cross hatching over up facing areas. It can also be avoided by reorienting the part. However this is still a problem over large flat areas or shallow slopes and care must be taken when breaking out the part. [13, 14].

Advantages :-
Relatively cheap machines
Cheap materials
Clean safe materials
Good for large, thick, simple parts

Disadvantages :-
Manually intensive post processing
High maintenance and set up time
Poor for thin walls and small features
Learning time
Laser cut

Laser cuts out first layer and
hatches waste material.

Table moves down and
fresh paper feeds over part.

The table moves up and the
heated roller adheses the new
paper in place ready for the
next layer to be cut.

Figure 2.1.4.3.1. Laminated Object Manufacturing.

Figure 2.1.4.3.2. Helisys LOM 1015.

Figure 2.1.4.3.3. Kira Corporation Solid Centre KSC-50.
2.1.4.4 Fused Deposition Modelling (FDM)

Principle

Thermoplastic material is fed in filament form to a heated extrusion head. Layers are made by molten material deposited as a fine bead, similar in principle to a scaled down ‘glue gun’. The build table lowers an exact amount and the next layer is deposited on to the previous layer. Interlayer bonding is due to partial melting at the boundary.

Detail

Parts are made by extruding plastic through a heated nozzle. See Figure 2.1.4.4.1. The nozzle moves in the x and y axes to produce layers. The build table then lowers by a layer thickness and the next layer is produced. Supports for overhangs are built up with the model and are removed when the part is complete. The materials are thermoplastics, such as ABS or Nylon, investment casting wax can also be used. They are fed in the form of a filament from a spool. The models produced therefore can be handled directly and require no cleaning or curing. The parts physical properties are close to injection moulded plastic parts and are therefore very strong compared to other RP parts. Removing the supports proved difficult due to the strength of the materials. This has been addressed by the use of a second material which is deposited as the support. This forms a weak bond enabling the supports to be easily removed by hand. [17, 18].

The process also means that the machine is very quiet and clean and is suitable for an office environment. Because the process is basic there are few moving parts and the machine is therefore easy to maintain and reliable. Surface finish and accuracy are not as good as SLA for example but the machine is around a third of the price of an SLA machine and parts cost around half as much to make. The machine can also accept Numerical Control (NC) code as input data. Similar technology developed by IBM is now owned by Stratasys and is used in a lower cost machine [17, 19, 38].
Advantages: - Relatively cheap to buy and run
Reliable
Clean and safe process
Strong parts in production materials

Disadvantages: - Poor accuracy and surface finish compared to SLA
Small features difficult

Figure 2.1.4.1. Fused Deposition Modelling.

Figure 2.1.4.2. Stratasys FDM 1650.
2.1.4.5 Selective Laser Sintering (SLS)

Principle

Similar to stereolithography except using powders instead of liquid resins. A powerful laser locally fuses, or sinters, particulate material. The build platform is lowered and fresh powder is applied and the next layer scanned on top of the previous layer. Local melting also forms an interlayer bond. See Figure 2.1.4.5.1.

Detail

Parts are made by selectively sintering powder material to solid using a CO2 laser (of around 50 W). The material has to be heated to near melting point and the laser locally heats the powder fusing the particles together. The build platform lowers each layer and fresh powder is spread across the build area by a roller. The inherent dangers of handling powders are controlled by purging the build volume with nitrogen gas. Models are supported by the unused powder. Build times are comparatively slow to allow for heat up prior to building, around 1.5 hours, and cool down of the powder after building, around 2 hours. When completed the part is broken out of the powder and bead blasted to remove excess powder adhering to the surface of the part. The machines are quite large and heavy and require extraction and the nitrogen supply [20, 21, 38, 50].

An advantage of laser sintering is the wide range of materials available. Theoretically any powdered material which melts can be used. This is especially true of the DTM machines which can use any of the materials developed for it. The EOS machines, however, are material specific. SLS machines currently use thermoplastic materials and more recently metal based materials. Plastic materials include polycarbonate and nylon. The polycarbonate parts are the most accurate as the particles do not fully melt reducing shrinkage. This does result in a porous part but they are strong enough for some functional work, including snap fits. Accuracy of polycarbonate parts is around ±0.4 mm, a little worse than SLA for example.
As was found with early SLA parts, curl can be a problem, especially over large thin areas in the build plane. This can be eliminated by building supports or anchors or reorienting the part. Nylon parts fully melt and show almost no porosity, these parts are therefore strong compared to other RP systems. Surface finish is poor compared to SLA, as may be expected from a powder, but material costs are slightly lower than SLA resins. There is also an investment casting wax material but it is problematic and little used as polycarbonate parts can be also be satisfactorily investment cast. Polycarbonate parts also build quicker, taking around two thirds of the time to build compared to wax. When installed it takes quite a while to set up the machine parameters, involving a certain amount of trial running. However once set up it requires little resetting. A new proprietary thermoplastic material called TrueForm™ has a very small particle size and low shrinkage, around 0.6%, yielding a much improved surface finish and accuracy. TrueForm™ parts are much closer to SLA parts in terms of accuracy and surface finish. TrueForm™ also requires much shorter warm up and cool down times. This material is also suitable for investment casting [25, 50].

The development of metal materials has proceeded along two different routes both aiming to produce short run tooling rather than functional metal prototypes. The system developed by EOS GmbH uses a proprietary low melting point metal powder developed by Electrolux. The material is sintered in one process in the dedicated EOSINT M machines. The parts produced are slightly porous and can be infiltrated with tin. Poor surface finish maybe a concern and the tool face will need a certain amount of machining and polishing to be acceptable for injection moulding. Injection mould tools made this way should be able to produce a few thousand shots. As with the DTM machines tool size is limited to the build envelope of the machine. EOS sells two machines the M250 and M160 with build volumes of 250 x 250 x 150mm and 160 x 160 x 120mm respectively [26, 53].

The system developed by DTM Corp. uses an iron based powder which is coated
in a polymer binder. The machine sinters the binder to produce a “green” part. This can be done on an existing Sinterstation 2000 or 2500 with some minor modifications to compensate for the increased weight of the material. The binder requires less energy to fuse than sintering plastics due to the thermal conductivity of the metal and the comparatively small amount of binder material which has to be melted. Therefore the build volume is not heated. Once the part is complete the binder is burned off in a furnace and the metal particles partially sinter to produce a “brown” porous part. This porous part is infiltrated with a low melting point copper alloy to produce a fully dense part. The finished part has characteristics similar to tooling Aluminium (7075) and can be machined. As with the EOS system poor surface finish maybe a concern and the tool face will need a certain amount of machining and polishing to be acceptable for injection moulding. The completed tools should take around 10 working days and have a tool life of around 50,000 shots [22, 50]. Partially successful attempts have been made to die cast into these tools. [78]

EOS have recently developed a sintering machine which uses foundry sand to directly produce sand casting moulds and cores. DTM also recently announced a foundry sand material for use in its Sinterstation machines. These processes are described in Chapter 2.2.4.1. Unlike other RP routes, which require investment casting, parts intended to be produced by sand casting can be prototyped relatively quickly and produced in the production material by the production process [23, 50].

Advantages :-

Strong Parts
Reasonably accurate
Use of metals for short run tooling
Wide range of materials

Disadvantages :-

High cost of machine and materials
Large machine, requires nitrogen supply
Heat up, cool down time, and poor surface finish
Figure 2.1.4.5.1. Selective Laser Sintering.

Figure 2.1.4.5.2. DTM Sinterstation 2000.
2.1.4.6 Jetting Head Technology

Principle

Thermoplastic material is deposited discretely by jetting heads, like those used in ink jet printers. The material is ejected as a liquid, solidifying on contact with solid material or the build platform. The head moves in x and y axes to build the layers. The build platform lowers by a layer thickness and material is deposited on to the previous layer. See Figure 2.1.4.6.1.

Detail

The machines and materials are clean and safe and do not require extraction. Most machines build support structures but the Sanders machine surrounds the part with a second wax support material. It also uses a milling head to level each layer. Very fine control over this milling allows layers as thin as 0.013mm to be built. The Sanders machine uses a single deposition jet and consequently build times are very slow but an accuracy of around 0.025mm can be achieved [28, 29].

There are several companies producing small office based machines which also utilise deposition processes similar to those found in ink jet printers. These machines are intended to sit next to a CAD terminal and be as simple to operate as a printer. The Actua 2100 made by 3D Systems uses an array of 96 jetting heads to allow fast building of models. Unlike the ink jet type machines the Ballistic Particle Manufacturing (BPM) machine developed by BPM Technology Inc., uses a single piezoelectric jetting head with angular articulation as well as motion in x and y axes. As this is a slow build process models are built as a skin with an internal support structure. However, BPM Technology Inc. have now ceased trading. It is yet to be seen if their process rights will be used by another company. Stratasys now owns technology developed by IBM, similar in principle to FDM, and produces a lower cost, office based machine based on it. These machines are all priced between £45,000 and £60,000. [17, 27, 41].
These machines are not as accurate as expensive systems, like SLA for example, and they are intended more for the concept verification stage. With the exception of the Sanders machine which is proving popular with the jewellery trade due to their accuracy and suitable casting materials. Correspondingly the material strength and surface finish are not as good as SLA for example. 3D Systems and Stratasys suggest that their machines are for concept verification only and very high accuracy is not a priority. The aim is for the machines to be a computer peripheral and treated like a printer. To this end the build preparation software is completely automatic [2].

Advantages :-

Cheaper, small machines
Easy to use
Low maintenance
Suitable for office environment

Disadvantages :-

Lower accuracy and surface finish
Limited application
Figure 2.1.4.6.3. Sanders Model Maker II.

Figure 2.1.4.6.4. Sanders jetting head plotting mechanism.
2.1.5 RP in Japan

There are seven companies producing stereolithography machines in Japan but none are as yet available outside Japan. There is also one company producing a laminated object manufacture machine. Together they account for 82% of the Japanese market. There are around 150 machines currently in operation in Japan. The largest market share belonging to CMET with around 37% followed by D-MEC with 20%. The most notable import being 3D Systems with around 14%. It is unlikely that these companies will export in the near future, due in some cases to uncertainty over patents.

The expected sharp growth of the RP industry has been hindered by the recent economic recession in Japan. In contrast to the distribution of RP users in the USA the greatest proportion of RP use in Japan is in the electrical and electronic industries with little use in the automotive and aerospace industries.

On the whole they are technically similar to other stereolithography systems. Generally the software lacks development, taking hours to prepare data and having no support generation capability. Supports are added to the CAD model manually. The Japanese are also handicapped by very little usage of 3D CAD in industry. They have a reluctance to adopt CAD systems which are not designed in Japan. Even if they do it takes about two years to translate a CAD package into Japanese so they rarely have the latest release. On the other hand their resin development may well be ahead of that in the West with claims that they directly apply SL parts as injection mould tooling.

As in the USA and Europe research is being done on conversion to metal via investment casting, medical modelling and improved machine and software performance. Most of the research in Japan is concentrated on stereolithography based processes. As in the USA the success of medical modelling using RP depends greatly on the Medical Insurance companies approving of the process. [6, 43].
2.1.6 Direct Applications

2.1.6.1 Communication

RP models provide greater opportunity for communication across disciplines. A three dimensional model can be readily understood by people not used to interpreting engineering drawings. Key personnel which would benefit from increased communication could include; marketing, sales, manufacturing, assembly, distribution and perhaps most importantly tool makers. Models could also be used to improve communication between manufacturers or designers and clients, customers or end users.

2.1.6.2 Design Verification

Models created by RP processes are used for, form, fit and function checks. This is often for instance visual approval models, assembly checks or fit checks. Having the ability to check a design which is as intended, with correct draught angles and features, will give confidence in the CAD design before production tooling is cut. The speed of prototype production should also allow many more design iterations to be verified within a given schedule. Function tests however are limited to the physical properties of the RP build material, if the physical properties do not meet the required level a downstream process will be required to obtain a part in the production material or a close approximation (see Chapter 2.2. A Review of Rapid Tooling Techniques). Models can be finished and painted to various levels for display, prelaunch photography or market research.

2.1.6.3 Analysis

Transparent SLA parts can be used to analyse flow characteristics in complex tubing or channels. A fluid is transported through the model with some indicator of flow added, for example water with air bubbles. This has been done extensively in the development of auto engines, for instance flow in engine manifolds, cylinder heads, and water jackets has been analysed using SLA models [47, 51].
Epoxy stereolithography parts can be used for photoelastic and thermoelastic stress analysis using optical diffraction techniques. Other RP techniques can produce masters from which epoxy parts can be vacuum cast. This enables design optimisation before a metal part has to be made. This has been used by SNECMA on turbine blades and by Rover on con-rods [40, 42, 47].

2.1.6.4 One Off’s

If there is only a requirement for one or only a few parts, RP techniques could be an effective way of manufacturing them. These could be replacement parts for components no longer in production or replicas of objects too expensive to tool up for or too precious to handle. This could include for example historical or archeological pieces for display in museums. In this case an RP part is the finished item requiring no further tooling or hand production.

2.1.6.5 Medical Models

Because the Magnetic Resonance Imaging (MRI) and Computer Tomography (CT) scan data is layered computer data it can be applied to RP processes, mainly SLA or SLS for good accuracy. Specific software is required to create the build files and generate supports from the scan data (i.e. no STL files are produced). This software requires trained medical staff to interpret the scan data correctly. Also this software must interpolate intermediate layers as scans are usually only taken every 1 to 2 mm. Medical models are often of bone structures and used for patient communication or operation planning and practice.

RP processes can also be used to produce prostheses and appliances which will be specific to the patient. The ability to “mirror” an RP model can be used to produce left or right handed models to aid reconstructive surgery. A recent development enables coloured SLA parts to be made. By altering the energy levels applied to a special resin its cured colour can be altered. This enables, for example, different tissue types to be distinguished within a model [44, 48, 49].
2.1.6.6 Tooling

It is possible to create tools directly with RP techniques. These could be for example, an SL tool for injecting wax to create patterns for lost wax investment casting or for casting ceramic parts. LOM tools for example have been used as press tools, vacuum forming tools and blow moulding tools. With the advent of direct metal RP processes the direct production of tools for various uses will increase (see note). What kind of tools are possible is limited by the physical properties of the RP build material. As with RP parts, an RP tool can be applied to a down stream process to obtain a tool in the correct material.

This area is explored in greater detail in Chapter 2.2: A Review of Rapid Tooling Techniques.
2.1.7 Down Stream Techniques

Often the RP part itself is not suitable for direct use but enables production of parts in other materials, ideally the proposed production material or a material with similar properties. Downstream processes can also be used when more than one part is required and it would be uneconomic to produce multiple RP parts. It may be that the part has to be produced in a material whose performance closely approximates that of the proposed production material for a specific test, this is especially the case where metal parts will be required.

In most cases the RP model is used as a master pattern. This means the model must be very accurate and highly finished. With some of these processes shrinkage can become significant, therefore the RP models can be scaled to account for this.

Because of the layer building techniques the physical properties are not isotropic. The parts produced by downstream techniques are usually isotropic but may not match production versions because of mould flow characteristics, temperature changes or other production parameters.

The RP part may also enable the production of tooling capable of producing low production volumes or RP may be used to directly produce the tool.

2.1.7.1 Plastic Parts

Silicon Rubber Tooling

In this popular process an RP model is used as a master pattern. It is immersed in Room Temperature Vulcanising (RTV) silicon rubber, under vacuum to remove air from the rubber. When the rubber has solidified it is cut into two halves to release the master. The silicone is cut in such a way as to allow location of the two halves when they are put back together to form the tool. Two part polyurethane (PU) resins are used to produce the parts at low temperatures. PU resins can be graded to emulate almost any plastic, from elastomeric rubbers to rigid engineering plastics, this may
enable more accurate functional prototype testing. The reproduction is excellent and because the tool is flexible under-cuts can be accommodated, to a certain degree. However the PU reacts with the surface of the Silicon degrading it. This effectively determines the life of the tool. Normally around 20 shots can be expected. However the tools only cost in the region of a few hundred pounds so it may still be economic to produce several silicon tools rather than machine an aluminium tool for runs up to about a hundred parts [35].

Aluminium Filled Epoxy Resin Tooling

Similar to silicon tooling but uses rigid resins, usually aluminium filled epoxy resin. This means that undercuts cannot be done and draft angles and radii become important as in production tooling. Resin tooling may be used where more parts are required but not enough to warrant aluminium tooling. Many hundreds of shots may be possible. Resin tooling is around four times the cost of silicon tooling.

2.1.7.2 Metal Parts

Sand Casting

In this process RP parts can simply replace the traditional hand made or machined wooden patterns. In many cases RP parts will be more accurate than traditional patterns meaning a consistent gap can be achieved allowing consistent cast wall thicknesses to be produced. This is especially over complex curved surfaces. It also means critical features such as draft angles and radii can be faithfully reproduced rather than relying on 'eye judgment'. The use of RP also allows for shrinkage values to be taken into consideration. For example if the shrinkage for aluminium is 1.5% the RP pattern can be scaled up precisely so the finished casting is exactly as intended.

LOM patterns in particular are popular with foundries as they closely approximate traditional wooden patterns in weight and feel. If treated with care RP patterns should last just as long as traditional wooden patterns.
Precision Sand Casting

Is similar to sand casting in most respects except the sand is held in place by a resin binder. This means the patterns must eject from the moulds cleanly, requiring draught angles and suitable radii. RP patterns show the same advantages as those stated for sand casting [33].

Investment Casting

Originally RP parts had to be cast using Flask Investment casting. Flask Investment casting uses a very thick ceramic shelled mould held in a metal bolster. This technique could withstand the stresses caused by thermal expansion of RP models. The more common Shell Investment casting process uses a wax pattern which is covered in a ceramic slurry in successive layers until a shell of suitable thickness is created. The wax pattern is then melted out and the shell is ready for casting. Some RP patterns however swell considerably when heated and this often cracked the shells.

Once the metal is cast and cooled the shell is broken away revealing the casting. Surface finish is very good and complex parts can be made. The accuracy and finish are dependent on the original pattern. Using sacrificial RP patterns eliminates the need for mould tools which are traditionally used to create wax patterns. During prototyping this can greatly reduce lead times and costs [30, 31].

These problems have been approached differently by the RP system manufacturers. Some use wax materials similar to investment casting wax and others use modified foundry processes to successfully cast metals. Most of the casting done to date with RP models has been in aluminium but a variety of metals have been cast including Inconel, nickel, bronze and titanium [2].

To combat the problems associated with casting RP patterns modifications to material or build style have been applied by the RP system manufacturers. In addition
foundries have altered their processes to optimise the casting success rate. The DTM Sinterstation, Sanders and Stratasys FDM can produce RP parts directly in investment casting wax materials or materials with similar properties [17, 20, 28, 29].

SL parts show a high coefficient of thermal expansion and if treated like wax patterns expand greatly and crack the ceramic shell. This is combated by producing a hollow structure which will collapse in on itself on heating. For example, 3D Systems QuickCast and EOS Skin & Core build styles. Since these materials do not melt the patterns can be burnt out [4, 32].

LOM parts will also burn out without cracking the shell as they do not show any significant expansion with heat. Ash residue of a few percent must be removed with water or air. To produce high quality castings consistently, the foundry must be prepared to learn the necessary process modifications. This is likely to include burning with excess oxygen instead of steaming and modified gating arrangements. The temperatures and times for the various steps will need to be altered and the shells made thicker than usual [11, 14].

If a greater number of castings are required it is possible that RP processes could be used to create an injection mould tool to mass produce wax patterns. The wax is not very abrasive and can be injected at relatively low temperatures and pressures, (around 50-55 degrees C). However the RP tool is likely to require backing usually in the form of metal filled epoxy. Again shrinkage values for both the wax and metal can be accounted for before the parts are built.
2.1.8 Benefits

The obvious and most important saving is time. In many industries today product development has to be faster as product life spans decrease. The increased communication possible is another major benefit. This is especially true across disciplines where the ability to read engineering drawings is not common. The other advantage of faster development operations is the ability to complete more design iterations before launching a product thus increasing its quality and probable success. RP may also prevent errors from reaching the tooling or production stage saving time and money on tool returns. RP generated parts are likely to be more accurate than hand made models especially where draught angles and complex curves are required. The ability to accurately produce complex shapes may open new product design, ergonomic and styling opportunities to some companies, especially those involved in specialist or low volume markets.

There will be greater time and cost savings as rapid tooling becomes reliable and more widely applied. Time and money savings could be very significant making some products viable in production processes which were previously uneconomic. Currently rapid tooling is only being applied to preproduction quantities but with a growing industry trend towards smaller production runs of niche products with correspondingly shorter life spans these methods may well become production methods for these smaller volumes.

A spin off benefit is the encouragement to adopt three dimensional solid CAD. The advantages of integrity of data transfer mean mistakes from interpretation and approximation are eliminated. If a part is designed on a solid modeller and an RP parts checked and approved the same CAD data can be safely used to generate the tooling for the part. This is in addition to the other benefits associated with solid CAD data including stress analysis, flow analysis, mass properties etc.
The general benefits of RP can only increase as the industry develops and the accuracy and cost of the processes improve. The market already shows signs of diversification with machines lending themselves to more specific applications and this will undoubtedly increase with time. The industry is growing very fast, faster than for example the CNC market has, and as with other markets a few companies may dominate the market.
2.1.9 Future Development

Systems

There needs to be a greater awareness of the potential of RP in industry and design, especially amongst the users of bureau services. Bureaux could improve their quotation systems so there is more consistency across the market and more consistent costings can be estimated. There needs to be more foundry education and involvement in casting processes. More widespread use of 3D CAD in all areas of industry would also give greater possibilities in other areas outside RP. The machines and associated techniques will need to be developed to the point where they are reliable and consistent with little maintenance required to ensure accurate and predictable results.

The RP market will probably segment, leading to diversification of processes. There will probably be one market for concept modeller and another for industrial machines. Concept modeller are smaller, low cost office based machines which should be; safe, require no special skill to operate, with perhaps less emphasis on accuracy. Industrial machines are more expensive, with larger build volumes, are more accurate, factory or lab based, and less safe requiring training and skill to operate. The small office based machines may be used by designers to quickly verify concepts and early design iterations. When final models for fit and assembly checks are required accurate models may be produced by RP bureaus on high level machines [50].

As with most developing industries companies may fold or merge and it is possible that some of the systems may cease production. This has already been seen with the acquisition of the EOS GmbH stereolithography business and Keltool Inc. by 3D Systems Inc. and the recent demise of BPM Technology Inc. There may well be no new companies embarking on developing new RP processes because of the investment required and the growing established market becomes more difficult to break into. It is more likely that new technologies will be introduced by the existing companies as they try to consolidate their position or establish a broader range of
products and services. There may also be machines developed for specific applications or industries.

Related Areas

There are cases where RP has served to illustrate deficiencies in other areas of a company’s product development procedure. Reducing the time required to manufacture prototypes may make other development processes appear longer. Also forcing people to use 3D CAD may show other benefits of using computer data, namely less mistakes from poor interpretation, the use of computer simulation such as Finite Element Analysis and direct application of the CAD data to the production of tooling. Therefore, there are indirect benefits from implementing RP techniques.
2.1.10 Market Details

It is estimated that there are around 3400 RP machines now in use in the world, the majority of which are located in the USA. There are currently around 130 machines in the UK. A pie chart showing the approximate global distribution of these technologies can be seen in Figure 2.1.10.1. Charts showing the UK breakdown of systems and machines can be seen in Table 2.1.10.2 [34].

Figure 2.1.10.1. Proportion of RP machine type in the UK.
<table>
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<th>System Type</th>
<th>Manufacturer</th>
<th>Number</th>
<th>Market Share</th>
</tr>
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<td>3D Systems Inc.</td>
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<td>EOS GmbH.</td>
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<td>1.36%</td>
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<td>DTM Corp.</td>
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<td><strong>9.52%</strong></td>
</tr>
<tr>
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<td>Hellsys Inc.</td>
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<td>6.80%</td>
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<td>Sanders Prototype</td>
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<tr>
<td>FDM</td>
<td>Stratasys Inc.</td>
<td>32</td>
<td>21.77%</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>32</strong></td>
<td><strong>21.77%</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>147</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Table 2.10.2. RP Machines in the UK, 1998.
2.1.10.1 Stereolithography

The majority of RP machines in the world are stereolithography systems accounting for about 44% of the global market. This was the first type of system to be developed and commercialised by 3D Systems based in California, USA. They currently hold about 40% of the world RP market and account for the vast majority of SLA systems sold. A smaller number of SLA machines were also produced by EOS in Germany and various companies in Japan. However, none of the Japanese companies has yet exported any machines and the stereolithography business of EOS has been acquired by 3D Systems, ending legal disputes over patents relating to the stereolithography process. There are over 60 machines of this type in the UK and as many as 1500 world wide. [34, 6].

2.1.10.2 Solid Ground Curing

This system developed in Israel by Cubital is less common, accounting for only about 1% of the global market. There are around 30 machines in use in 15 countries but there are none in the UK.

2.1.10.3 Laminated Object Manufacture

First developed by Helisys who are based in California, USA. LOM is the second most common process. There is also a manufacturer in Japan, Kira Corp., although they have not yet exported in large numbers. A basic LOM machine is also made by Sparx AB, based in Sweden. There are over 314 Helisys machines in use across the world, 10 of which are currently in the UK. Although there are plans to import Kira machines to the UK there is currently only one Kira machine in the UK being used as the importer’s demonstrator. LOM machines account for around 10% of the global market [41, 6].
2.1.10.4 Fused Deposition Modelling

Established in the USA, Stratasys Inc. is the only producer of machines using this technology. It is less common than SLA but is comparatively cheap and reliable. The scope has recently been increased with the introduction of the Genisys concept modeller and a larger FDM 8000 and Quantum machines. There are over 1000 machines in use world wide with around 32 located in the UK, of which 5 are Genisys concept modellers. FDM accounts for around 30% of the RP systems currently in use in the world [6, 34].

2.1.10.5 Selective Laser Sintering

Two companies produce SLS machines, DTM Corp. in Texas, USA and EOS GmbH in Germany. There are over 250 SLS machines in use world wide accounting for around 8% of the global market. There are currently 14 DTM machines in the UK [6, 34].

2.1.10.6 Jetting Head Technology

Companies producing systems like these include BPM Technology, Sanders Prototype and 3D Systems Inc., all from the USA. All these machines are intended to compete in a cheaper market place than existing RP machines, around £35k to £50k. BPM Technology Inc. has recently folded and it remains to be seen what will happen to the ballistic particle manufacturing process. There are around 7 3D Systems machines and 20 Sanders jetting head machines currently in use in the UK. Jetting technology machines currently account for only around 6% of the global market. This type of system is likely to become far more common as they are smaller, easier to use and considerably cheaper. There is also more scope for other manufacturers to enter the market as the technology is cheaper and less well protected by patents [6, 34].
2.2 Rapid Tooling Technology

2.2.1 A Brief History of Rapid Tooling

Since the advent of Rapid prototyping the logical next step was to apply time reducing technologies to the production of tooling. As the production of tooling is perhaps the largest single commitment in terms of cost and time in product development any reductions in this area could prove significant. As it is not economic to produce large numbers of rapid prototypes various replication methods have been employed to generate runs of prototypes from below twenty to many thousands. These methods are often referred to as Soft Tooling.

With the growing trend towards niche products product life spans decrease and therefore production volumes decrease to the point where the difference between a low volume production run and a large prototype run can be quite small. Therefore tooling methods previously intended to produce large prototype runs are now being applied to smaller production runs.

Many of the basic principles used in creating rapid tooling have been around for some time in other areas of industry. With some of these processes the main problem was the creation of a suitable master pattern from which the tool can be made. Construction of an accurate detailed master pattern by traditional methods is a long and costly process. Often, this could be as time consuming and costly as creating tooling by traditional methods. Rapid Prototyping has facilitated the production of accurate master patterns within an acceptable time and cost enabling the economic use of these methods in the creation of tooling.

Some rapid prototyping techniques have been developed to use materials which allow the direct building of tooling. At the moment these tools are limited to smaller production or prototype volumes. Direct building of production tooling is seen as a principle aim of research into many areas of rapid prototyping technology [77].
2.2.2 Areas of Application

There are various reasons for utilising rapid tooling. It may be used to produce a small run of preproduction prototypes to prove the design or manufacturing of a new product. Or it may be the case that the rapid tooling is used to produce the initial production run so that a product can be launched while full production tooling is still being made. This is sometimes referred to as bridge tooling. Alternatively as is increasingly the case rapid tooling could be applied to low volume production runs of niche products. Methods that in the past have only been used as preproduction, or soft tooling, are now being applied to production volumes.

Generally speaking rapid tooling involves some compromise between the properties of the final tool and the speed at which it can be produced. Often the materials used will have poorer tensile strength and thermal characteristics in comparison with traditional steel tools. Consequently each process will have limits of geometry and service life [54].

In most of the Rapid Tooling methods the amount of RP process time is limited by only producing the minimum requirement. This usually means only using rapid tooling processes for the creation of the tool face or the inserts which form the actual geometry. Therefore, common to a lot of rapid tooling processes is the use of standard bolsters and precut pockets in tool steel. These may include the cooling channels and feeds, runners, sprues and gates. The use of the steel pocket not only reduces the rapid tooling process time but also helps enclose and strengthen materials which are usually weaker than tool steel. Another common procedure is the use of cast backing up materials. These are used when the rapid tooling method only produces the tool face and the bulk of the tool material is cast against it. Aluminium filled epoxy resin is commonly used for this. Chemically bonded ceramic material and cement can also be used.
Rapid tooling can be applied to many areas of tooling. For example, rapid tooling has been used to create tooling for pressing, rotational moulding, blow moulding, vacuum forming, wax pattern moulding and injection moulding. However, most of the developments have been targeted at the more cost critical manufacturing processes such as the injection moulding of plastic components.
2.2.3 Rapid Tooling Methods

The various techniques can be broken down into three sub groups. They are;

2.2.3.1 Methods Requiring Master Patterns

These processes involve creating a tool by forming material over a positive model of the finished article. These master patterns may be simply a model of the part or may incorporate parting planes and other tool details.

2.2.3.2 Methods Involving Direct Production

These processes involve directly producing the tools or tool faces using rapid prototyping processes.

2.2.3.3 Methods Involving Indirect Production

These processes involve conversion of tools built using rapid prototyping processes into a suitable tooling material.

There follows a description of the common processes in each of these groups.
2.2.3.1 Methods Using Master Patterns

Vacuum Casting or Silicone RTV Rubber

Vacuum casting is extensively used in conjunction with rapid prototyping. It is used to create small numbers of parts which closely approximate injection moulded plastic components. The process is widely used and standard semi-automated machinery is available as are a wide range of materials.

In this process an RP model is used as a master pattern. A silicone rubber tool is made by immersing the master pattern in Room Temperature Vulcanising (RTV) silicone rubber. Vents and feed channels are added to the master pattern. This is done under vacuum to remove air bubbles from the silicone rubber. When the rubber has solidified it is cut into two halves to release the master. The silicone is cut in such a way as to allow location of the two halves when they are put back together to form the tool. See Figure 2.2.3.1.1.

![Figure 2.2.3.1.1. Silicone Rubber Tool and Vacuum Cast Part.](image)

Two part polyurethane (PU) resins are used to produce the parts at low temperatures. PU resins can be graded to emulate almost any plastic, from elastomeric rubbers to rigid engineering plastics, this may enable more representative functional prototype testing. The resin is introduced into the mould under vacuum to remove air bubbles from the resin and ensure the tool is filled.
This is then cured for around 45 minutes in an oven before the tool is separated and the moulding removed. The vents and any flash are then cleaned from the part. The reproduction is excellent and because the tool is flexible under-cuts can be accommodated, to a certain degree. However the PU reacts with the surface of the Silicone degrading it. After several cycles the silicone becomes rigid and opaque and will eventually crumble. This effectively determines the life of the tool. Normally around 20 shots can be expected. However the tools only cost in the region of a few hundred pounds so it may still be economic to produce several silicone tools rather than machine an aluminium tool for runs up to about a hundred parts.

Machined metal inserts can be incorporated to produce tall thin features or critical bores. The parts themselves cost around £30 to £40 each for small parts. A great proportion of the cost is due to the manually intensive nature of the moulding process. Usually it would take around a day to produce a tool and after that around 6 shots can be performed in a working day. Alternatively multiple impression tools can be made if the parts are small [55, 56, 57].

**Spin Casting**

Spin casting involves the use of silicone rubber tools to cast metal components. The castings replicate small die castings and use Zamak, zinc based alloys. Investment casting wax can also be cast using this method as can PU resins as used in vacuum casting [58].

The silicone moulds are disc shaped and cast around RP master patterns. These moulds are made from High Temperature Vulcanising (HTV) rubber. This material is in disc form and is putty like. A rough cavity is carved out and the master pattern placed in. The discs are then clamped and cured under high temperature and pressure. The rubber locally liquefies and then cures to solid. The material is separated and the master patterns are removed to reveal a precise moulded cavity. Due to the higher temperatures and pressures exerted on the master patterns during the moulding
process they may be damaged. Feed channels are carved to each cavity from the centre of the disc. This HTV silicone rubber is more durable than RTV rubber and better withstands the casting process. See Figure 2.2.3.1.2.

![Figure 2.2.3.1.2. Spin Casting Mould and Cast Zinc Parts.](image)

The mould is held between two steel plates and spun, between 200 and 1000 rpm. The metal material is fed from the centre of the tool and the centrifugal force fills the cavities. The tools should be able to maintain accuracies around +/- 0.3 mm. Lead times are around 10 to 15 days to produce the tool and the first 25 shots. The tools cost in the region of a few hundred pounds and the castings cost around £10 to £15 each. More than 30 shots should be possible from each cavity. The cavities should be arranged in opposed pairs to balance the disc tool. The size of the casting is limited to around 100 x 150 x 70 mm as control of the tolerances gets difficult beyond this size due to contraction [59].
Aluminium Filled Epoxy Moulding

This process is very similar to vacuum casting except the tooling is a dense rigid material, usually Aluminium filled epoxy resin. In this process the RP master pattern has metal filled epoxy resin moulded around it, one mould half at a time. When the resin hardens the RP model can be removed. The cast tool halves are left overnight to cure. Heat is generated by the curing process as is a small amount of shrinkage and the RP master pattern may be damaged when it is removed from the cavity.

Once produced the tools can be used to cast PU materials under gravity or under vacuum. These tools will not react with PU resins and therefore should be able to produce many mouldings before the tool degrades.

Alternatively these tools can be placed in a bolster and used in injection moulding machines. Surface reproduction is good but the tools are relatively soft and do not wear well. The tools also do not have good tensile strength so draught angles and radii have to be generous if the tool is to survive many shots. As with other cast tools machined inserts can be fitted to produce tall thin features and bushes for ejector pins. The thermal properties are also not as good as a metal tool and therefore plastic injection moulding tools are not very successful and cycle times have to be lengthened accordingly. Cooling channels may be cast into the tool by placing copper tubing around the pattern. Potentially a few hundred shots will be possible with care and an unfilled thermoplastic such as polypropylene.

Another use for these tools is injection moulding of investment casting sacrificial wax patterns. The wax material is less demanding and many hundreds of shots should be possible. These tools may also be successfully used for low pressure moulding processes such as Reaction Injection Moulding (RIM).

Aluminium filled resin tools, when sufficiently backed up, are good for press tooling due to good compression strength. Thousands of pressings should be possible.
depending on the pressed material. This process has, for example, been successfully applied by Rover to press aluminium door skins [54, 55, 57].

**Spray Metal Tooling**

In this process the RP model is used as a master pattern onto which atomised molten metal is sprayed. The metal used is usually a low melting point alloy. Alloys used include lead/tin (solder) and alloys consisting mostly of zinc. The most common method of metal spraying for use in tooling is arc spraying. In this method the material is fed in the form of wires and an electric arc is struck across them melting the material, see Figure 2.2.3.1.3. The molten material is atomised and projected towards the pattern by compressed gas. The equipment costs are reasonable and the surface reproduction is good. However the mechanical strength is low and the sprayed shells show a slightly porous surface.

![Figure 2.2.3.1.3. Spray Metal Tooling.](image)

The High Velocity Oxygen Fuel (HVOF) method allows higher melting point materials to be sprayed, including steel, and there is almost no porosity. However the equipment costs are higher. The use of higher melting point materials may also mean a secondary master pattern has to be created in a material capable of withstanding those temperatures. This process may negate some of the time saving advantage of making the spray metal tools. Also the more replication steps there are in a process the more inaccuracies will be incurred [57, 60, 61].
The sprayed metal is built up to a certain thickness, usually several millimetres, and the bulk of the tool is backed up using metal filled epoxy or chemically bonded ceramic. Care should be taken to avoid air bubbles in the backing material as they will be hidden from view behind the sprayed shell and may collapse under moulding pressures. Cooling channels made from copper pipe can be cast in at this point. Tool production should take around a day for each half, plus some machining time for ejector pins and skimming the mating faces.

Surface reproduction is very good, but due to the sprayed metal’s properties the tools are not hard and wear quickly, especially at split lines. The deposited material has microscopic laminations formed from successive layers of sprayed metal and these will affect the strength of the material, especially at the split line. Most of the damage likely to be incurred during use will be caused at the split line when the moulding is ejected. This will be visible as chips at the corners where the cavity meets the split line. As the strength of the material is not great draught angles and radii should be generous to minimise tool damage. Draught angles need to be greater than 2 degrees. Critical areas can be achieved by locally using machined inserts, usually made from brass. Runners for ejector pins are can be produce this way too.

Despite these limits sprayed tools will allow a good number of prototypes to be produced in the production material, somewhere between 1000 and 2000. PERA for example claim up to 2500 shots are possible from their spray metal injection mould tools. The thermal characteristics will not be as good as those of steel tools and lower clamping pressures, longer cycle times and careful setting up will be needed. The life of the tool can be extended by plating the surface with nickel, however this adds time and cost to the process [54, 55, 62]

Spray metal tools are very quick to make, taking little more than a day. As with cast tooling methods machined metal inserts can be incorporated where tight draught angles or tall thin features are required. These inserts are usually made from brass and
are located on the master pattern and the metal is sprayed onto them incorporating the inserts into the sprayed shell. These inserts also have a greater tensile strength than the sprayed material. Deposition of material into deep narrow features may be difficult and “line of sight” is required. As with paint spraying material deposition will be thinner at external corners and thicker at internal corners [60].

Hard production tooling can be made by spraying nickel based alloys, surface reproduction is also very good. Nickel has very good hardness and toughness and is resistant to abrasion making production volumes possible. As with zinc spray tools cooling channels can be incorporated. The sprayed shell is backed up with chemically bonded ceramic which has a compression strength comparable with steel. However the higher spraying temperatures may exceed the glass transition temperatures (or melting points) of some of the rapid prototyping materials. Any softening of the master pattern will adversely affect the resulting tool.

Research has been carried out into the possibility of forming sprayed metal tools using steel. The high temperatures involved mean that a secondary pattern has to be created in a ceramic material and the steel is deposited onto this. This is difficult due the stresses induced as the steel is deposited and cools. These stresses cause the tool to deform. One of the possible ways of combating this is by simultaneous shot peening of the deposited steel. More work is needed before this process is commercially available [60, 63].

**Electroplating / Electroforming**

An RP master pattern can be painted with a conductive material, usually silver loaded paint, and plated in standard electroplating baths. The plating material is usually Nickel. This produces a very hard tool which will wear well, many thousands of shots will be possible. However the process takes a long time, a week or two, to build up a reasonable thickness. There can be deposition problems on internal and external corners and deep narrow slots may be difficult to form. As with spray tooling the shell
is usually backed up, often with metal filled epoxy resin. Chemically bonded ceramic can also be used as a backing material, see Nickel Ceramic Composite tooling below. Electroplated tools have been successfully used for RIM moulding and are commonly used for moulding shoe soles. Electroformed shells are also used for rotational moulding [54, 55].

Chemically Bonded Ceramic Tooling

Similar in approach to Aluminium filled epoxy tooling, except a ceramic material is cast around the master pattern. The ceramics have good compression strength but poor tensile strength limiting the geometries possible. The thermal properties will also be poor but this may be aided by adding metal fillers. An additional facing material may be used, see Nickel Ceramic Composite tooling below. Unlike the spray metal method it is a relatively cool process allowing RP master patterns to be used without fear of deformation of the master pattern due to heat. This process is still being developed but may be suitable for various processes including RIM moulding, injection moulding and press tooling [54, 55, 64].

Nickel Ceramic Composite Tooling

Developed by the CEMCOM corporation Nickel Ceramic Composite tooling (NCC) is a combination of an electroformed Nickel shell backed up with a ceramic material. It is intended to be a rapid tooling route for larger parts and be capable of producing intermediate numbers of shots, up to around half a million. The tools consist of a electroplated nickel shell forming the tool face backed up with chemically bonded ceramic material. In most cases the nickel tool face shows good detail and finish and is very hard wearing. The ceramic backing material shows very little shrinkage when it is cured and has reasonable thermal characteristics.

Whilst it is not as conductive as steel tooling it has better thermal characteristics than Aluminium filled epoxy backing material. Its compression strength is also very good transferring the loads from the nickel shell to the bolster. The thermal
coefficients of expansion (CTE) for the steel mould frame, nickel shell and ceramic backing are closely matched to minimise any stresses in the tooling during moulding.

The process involves electroforming a nickel shell over an RP master pattern incorporating a split line. The pattern is also fixed inside steel rings. These aid location into a steel mould frame. The deposition should take about a week to build up a reasonable thickness. The thickness required is less than for other electroplated nickel shells due to the strengthening effect of the ceramic backing. The ceramic backing is then vacuum cast into the mould frame. One side is done and left to cure over night then the other half is filled. When both halves are cured they are separated and the pattern is removed. Any final finishing can now be carried out.

The finish will depend upon the finish of the master pattern but any internal areas which may have been difficult will be transferred to the external surface of the tool simplifying any further finishing the tool may require. Some slight bowing of the split line may have occurred during the plating and this must be corrected at this point. See Figure 2.2.3.1.4.

![Diagram of High Strength Ceramic Backing](image)

Figure 2.2.3.1.4. NCC Tool Layout.

The process is not completely developed and further trials will prove whether it can be truly effective for a range of geometries and materials [65, 66].
3D Keltool

This proprietary process, now owned by 3D Systems Inc., involves casting a steel particle/binder mixture against silicone rubber patterns which in turn have been cast from an RP master pattern. The binder/steel cast tool is fired to burn off the binder and sinter the steel particles. Care must be taken when the cast material is removed from the silicon mould as at this point the material is delicate. Tall thin features therefore may prove difficult. As with SLS tools the porous steel tool is then infiltrated with molten copper. The resulting tool is approximately 70% steel and 30% copper. The tool inserts produced are hard wearing and have good thermal characteristics. 3D Systems claim up to a million injection mouldings are possible using these inserts.

Surface finish is however, superior to SLS tools due to the fact that the tool surface is determined by the silicone mould surface, which is in turn dependent upon the surface of the RP master pattern. It would be more often the case that finishing the exterior surface of an RP master pattern would be easier and quicker than machining and polishing the internal details of an SLS tool.

As with other multiple step processes care must be taken to allow for the shrinkage values of the production material and the tooling material. Precise control of the firing of the inserts maintains acceptable accuracy. However, control of this process imposes a tool size limit of 150mm in all three axes. This effectively limits the process to mouldings which are smaller than 100mm [55, 56, 67].

2.2.3.2 Methods Involving Direct Production

Selective Laser Sintered Tools

Selective laser sintering is an established Rapid Prototyping process using scanning lasers and powder materials. A powerful laser locally fuses or sinters particulate material. The build platform is lowered and fresh powder is applied and the next layer scanned on top of the previous layer. Local melting also forms an
interlayer bond. The nature of this process means that many materials are available providing they melt and can be formed into a fine powder.

The development of metal materials has proceeded with aim of directly producing short run tooling rather than functional metal prototypes. The system developed by EOS GmbH uses a proprietary low melting point metal powder developed by Electrolux. The material is sintered in one process in the dedicated EOSINT M machines. The material experiences no net volume change as it forms an alloy from its components which has a lower density, so the material expands as the alloy forms compensating for the shrinkage due to melting. This means the build volume does not need to be temperature or atmosphere controlled. The parts produced are slightly porous, about 70% dense, and can be infiltrated with tin, lead/tin alloys or epoxy resins.

Poor surface finish maybe a concern and the tool face will need a certain amount of machining and polishing to be acceptable for injection moulding. Injection mould tools made in this way should be able to produce a few thousand shots. As with the DTM machines tool size is limited to the build envelope of the machine. EOS sells two machines the M250 and M160 with build volumes of 250 x 250 x 150mm and 160 x 160 x 120mm respectively [68, 69].

The system developed by DTM Corp., called RapidTool LR, uses an iron based powder which is coated in a polymer binder, the scanning laser melts the binder to produce a “green” part. This can be done on an existing Sinterstation 2000 or 2500 with some minor modifications to compensate for increased weight of material. The binder requires less energy to fuse than sintering thermoplastics due to the thermal conductivity of the metal and the comparatively small amount of binder material which has to be melted and therefore the build volume is not heated. This means the heat up and cool down times normally associated with the SLS process are eliminated. Once the “green” tool is complete it is immersed in a photopolymer and cured. This is
because the green tool as taken directly from the machine is delicate, therefore great care must be taken when removing the green tool from the powder cake.

Tall, thin features and sharp corners especially may be damaged at this point. The green tool is then fired in a precisely controlled manner. The binder is burned off and the metal particles partially sinter to produce a “brown” porous part. This porous part is then infiltrated with Copper to produce a fully dense part. Over the whole process shrinkages should be limited to a uniform 2%, this is accounted for in the scaling of the STL file prior to building. The final tool consists of 60% Steel and 40% Copper. It is claimed that the finished tool has characteristics similar to tooling Aluminium (7075) or P20 Steel. See Figure 2.2.3.1.5. [70].

As with other SLS parts, the surface finish may be quite poor and the tool face will need machining and polishing to be acceptable for injection moulding. As much as 0.5 mm must be added to critical faces to allow for machining. The finishing may be difficult and time consuming depending on the geometry in comparison to replication methods where the surface finishing is performed on the master pattern. The completed tools should take around 10 working days and have a tool life of around 50,000 shots using engineering plastics. Injection moulding on these tools should be relatively straight forward as the tensile strength is comparable with Aluminium and the thermal characteristics are good due to the high copper content [70].
Another limiting factor is the build volume of the SLS machines. For example the DTM RapidTool process is limited to tools that are 150 mm by 250 mm.

An alternative short run process, called RapidTool SR, uses the same initial steps but infiltrates the porous “brown” tools with epoxy resin rather than copper. These tools should yield a few hundred shots. The process is slightly quicker and cheaper than producing copper infiltrated tools. Injection moulding into these tools would require care as the thermal properties and tensile strength will be significantly poorer than traditional steel tools [70].

These processes appear to be aimed primarily at injection moulding but could easily be applied to many other uses. They may, for example, be suitable for use as EDM electrodes. See below. Careful thought must be given as to whether producing metal tools is the most economic use of the SLS machine compared to using build time to produce models. In the case of the EOS machines they are dedicated to one material [71].

Direct Production of Sand Cores and Moulds

EOS and DTM have both developed processes which use foundry sand to directly produce sand casting moulds and cores. The material used by EOS is supplied by Croning and has a polymer binder. In the conventional Croning casting method hot steel tools are used to fuse the sand to form a solid mould. The energy required to fuse the binder is low compared to that required for sintering plastics and consequently laser scan speeds are quite fast and there is no heat up time required. Two machines are available with different build volumes, the smaller machine uses a 50 W CO$_2$ laser and the larger machine uniquely uses two 50 W CO$_2$ lasers each scanning half the build area. There is special software to ensure correct sintering at the join between the two areas.

Once created the moulds and cores can be treated exactly as ordinary casting
moulds. As with other SLS materials the EOS machine is dedicated to one material and the DTM sand will be available to existing Sinterstations [69, 70, 71]. Again, as with other SLS processes the surface finish will be relatively poor but is more or less comparable with traditional sand casting finishes.

Unlike other RP routes, which require investment casting, parts intended to be produced by sand casting can be prototyped relatively quickly using the production material and process. Therefore prototypes produced this way will have the correct metallurgical properties. The direct forming of sand moulds and cores could improve prototyping times for complex sand castings, such as engine blocks.

**Direct RP Tooling**

It is possible to produce tool inserts directly by RP processes which can be used in injection moulding. This has been successfully accomplished with SLA inserts and is referred to as Direct ACES Injection Moulding (AIM). The SLA material is comparatively brittle with poor thermal characteristics and therefore lower pressures, temperatures, extremely long cycle times and release agents are required. These altered parameters may affect the properties of the moulded component. For example, the production of amorphous plastics depends on rapid chilling of the molten plastic in the mould. Over long cycle times may lead to unwanted crystalinity in these cases. Even when great care is taken only a hundred or so shots will be possible. Solid tools would require long build times and consideration must be given as to whether it is the most economic use of the RP machine in question.

To reduce build time and aid the thermal characteristics it is possible to build only a shell of the tool face on the SLA and back fill the remainder with Aluminium filled Epoxy resin [56, 67].
Rapid Dies for Wax Patterns

It is possible given the lower temperatures and pressures involved to inject investment casting wax into tools made by RP processes. The solid CAD model of the product is used to produce solid models of tool parts. The tool parts are then produced in the RP material but usually backed up in for example an aluminium frame. Wax can then be injected to produce multiple wax patterns for investment casting. Around a hundred parts can be produced in this way [72].

2.2.3.3 Methods Involving Indirect Production

Rapid EDM Electrodes

A great deal of tool production time can be attributed to the production of electrodes for Electro Discharge Machining (EDM). Machining of EDM electrodes can account for up to 50% of the lead time of a tool produced this way. They are normally machined from copper or graphite. A quicker route would be to use an RP model electroplated with copper using the same plating process as previously described. Again this takes quite a while to build up a reasonable thickness. As with electroplating to form tools there can be deposition problems especially at sharp internal and external corners and in deep narrow slots. These processes are still in the research stage. Carbon is an unlikely direct RP material as it does not melt and therefore cannot be sintered [55, 73].

One of the main problems with this route is damage caused to the RP substrate. due mainly to the heat produced during sparking. Therefore it may be the case that an electrode made this way could be used as a finishing electrode as the demands are not as great and it makes good use of the inherent accurate surface quality. Roughing electrodes are often used to remove the bulk material and these could be quickly machined without any surface quality [74].
Other methods of producing rapid EDM electrodes use indirect routes where the RP processes are used to create patterns from which the electrodes are produced. For example copper electrodes can be produced by sacrificial investment casting from an RP master. Metal spraying into an RP mould could also be used but the porous nature of the sprayed metal produces electrodes which wear unacceptably quickly [73].

With the development of direct metal RP processes and considering the high copper content SLS metal parts could possibly be used for producing EDM electrodes. These could be well suited to roughing electrodes where surface finish is less important. Copper plated stereolithography models can be used as finishing electrodes. Therefore a combination could be used to produce tools quicker.

**Investment Cast Tooling**

Most RP systems can produce parts suitable for use as sacrificial investment casting patterns. If the RP process is used to create a sacrificial pattern of the tools rather than the component a metal tool can be investment cast. This enables tools to be made very quickly compared to machining. The process involves using the CAD model of a product to produce a solid CAD model of tool halves or inserts. There are dedicated modules which enable this in many solid modelling CAD systems. RP is then used to produce sacrificial patterns of the tools suitable for investment casting. These parts are then cast to produce tools for injection moulding, dies for wax patterns or press tools.

Tools have successfully been cast in Aluminium and steel. Cast Aluminium tools can be machined and polished in the same way machined tools can enabling a high accuracy and finish to be obtained. It may also be the case that ejector pins and cooling channels may be added to the tool by machining. However the tool will not have the durability of a machined steel tool, with only up to a few thousand shots possible. On the other hand cast steel tooling is extremely hard and therefore as durable if not more so than machined steel tools. However, this hardness means the
tools are extremely difficult to machine or polish. It may be possible to alter the casting process to enable cast steel tools to be machinable, possibly by slow controlled cooling after casting. This would enable tools as good as those currently made by machining to be produced in a matter of a few weeks rather than months.

Time to create an investment cast tool could be around a quarter of that required for machining, similarly the cost could also be around a quarter of the cost of machining. Great care must be taken to allow for the shrinkage values of the intended production material and the cast metal in order to produce an accurate tool [67, 75].

2.2.4 Advantages and Problems

The application of these methods always involves some degree of compromise. The tools may be produced quicker and cheaper but their properties and service life will be limited. It is crucial therefore to assess the suitability of a rapid tooling route and fully understand all the implications and risks associated with them before embarking on producing tooling. Many of the methods used are newly introduced and therefore represent a certain risk compared to well established techniques.

2.2.4.1 Advantages

a) Speed of production. The time savings in product development could be significant. Tooling could be arrived at in as little as a quarter of the time associated with traditional techniques.

b) Cost. The processes and materials may be inherently cheaper, but in addition the time savings could have significant cost advantages associated with them.

c) Proving Performance. Prototypes may be produced using the production material and process within the cost and time frames that did not previously fall within an acceptable product development schedule. This allows accurate functional testing to be completed before a product is launched improving the overall quality of a
given product. Thus minimising risk of failure in service and possible warranty costs. It also allows the production process itself to be tested highlighting potential manufacturing problems prior to volume production. This could eliminate down time and production line alterations, the costs of which could be very significant.

d) **Opportunity.** The reduced cost and time may mean that production processes that were previously uneconomic, for a given product and volume, can be applied. This may result in products with higher aesthetic and functional properties. This may allow smaller companies to compete more favourably with larger competitors. The shorter time to market may also enable companies to exploit seasonal markets or beat competitors to launch. The rapid tooling could be used to produce the initial lead volume allowing early launch into the market place whilst full production tooling is still being completed (bridge tooling).

### 2.2.4.2 Disadvantages

a) **Limits.** All of these processes have distinct limits. These may be size, geometry or volume related. However, as long as these limits are fully appreciated and accounted for they may not present a problem.

b) **Risk.** Not all of these processes are fully established. As with any leading edge process problems are bound to be encountered. These risks should be appreciated before embarking on a tooling route. The risks should be balanced against the potential advantages compared to traditional (low risk) alternatives.

c) **Physical Properties.** Due to the different materials used in many rapid tooling methods the temperatures, pressures and cycle times may have to be modified. These modifications may adversely affect the physical properties of the moulded component [79, 80].
2.2.5 Future Development

It can be expected that the rapid tooling routes currently in use will be perfected and the processes will become fully understood and established.

2.2.5.1 Methods using Master Patterns

Development in these methods will be concentrated into two areas. Firstly, the improvement of the tooling methods and materials. Secondly, the improvement of the physical properties and strength of the RP master patterns.

Tooling methods will have to be improved to allow the use of harder wearing materials. These materials generally incur higher temperature processes and require greater levels of control to allow accurate tooling to be produced. An example of this is the research which is ongoing into steel spray metal tooling. Other methods which involve high temperature processing should also be improved to maintain accuracies throughout the heat treatments. For example the current size constraint of the Keltool process is due to the difficulty in maintaining accuracies during the furnace operations. This can be expected to be improved upon as the process is better developed.

The RP processes should improve to allow for more accurate and durable patterns for use in replication tooling methods. One of the key issues will be increasing the temperature stability of the RP materials to enable their use in producing secondary tooling at higher temperatures. Improved strength and toughness will also allow these masters to better withstand the physical demands of being used as a master pattern. The master patterns undergo a certain amount of stressing as the tooling material is due to shrinkage of the deposited material as it solidifies or cures. Master patterns are also often damaged when they are removed from the tool cavity. Stronger RP master patterns would allow multiple tools to be made using the same master pattern.
2.2.5.2 Methods Involving Direct Production

The direct building (in RP terms a matter of hours) of production capable tooling will be the aim of rapid tooling research in the near future. This will involve the development of better materials for existing processes and the development of new processes especially concentrated on the production of metal tools. Particular attention will be focused on the use of tool steels in these processes. Major work will be required to control the behaviour of the materials during processing (shrinkage) such that the exacting tolerances of production tooling can be achieved. In addition factors affecting the quality of the surface finish of the tool face will need to be addressed.

2.2.5.3 Methods Involving Indirect Production

This area shows the greatest scope for development especially in areas such as the rapid production of expensive consumable tools such as EDM electrodes. However methods are unlikely to be taken up by manufacturers until the quality of the tooling can be guaranteed and genuine cost savings are proven.
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3.1 Previous Work

Previously there have been attempts at developing rapid prototyping (RP) selection systems which are based on relational databases [1, 2]. The first approach uses a relational database-management system. In this approach a database of RP machines and materials properties is constructed with additional formulae for build time and cost. A user is required to specify details of the machine and materials to be used. The user also has to specify the orientation in which the prototype is to be built. The method of Benefit Value Analysis [2] is then used to evaluate various combinations of machine and material against the user’s requirements. An example of the evaluation is “First place, 83% of requirement degree, for the machine ABC with material XYZ” [2]. With regard to the aims of this study, there are two major drawbacks to this approach. Firstly the user has to have a working knowledge of both the RP machines and materials that they intend to use. Secondly, when in use many complex parameters have to be specified and entered by the user. This precludes the use of the system by users who do not have their own RP system but need to determine the best system in order to commission a prototype from a service provider. Typically these users are in small companies (small to medium sized enterprises or SME’s). In addition the reliability of the results are in question as they are not verified against the experience of expert users and therefore have little or no practical value to the target user.

The second approach is also developed on a relational database-management system. The structure of the database, however, differs from the first approach in that individual geometric features of the object are used as RP benchmarks. These features could be dimensions, holes, slots or even features which are specific to particular products. This means that RP systems are selected according to the specifications provided by the user and refined through an iterative process according to how well certain RP systems can recreate the features on the object to be made. The system is based on the hypothesis that “once the capability of an RP system has been determined for individual features its capability for any component containing these features can
be predicted” [2]. The monumental task of building a database that contains the values for every type of geometric feature built using every RP system would make the system unreachable in terms of cost to the casual user such as those in small companies (SMEs). Once completed, updating a system like this would also be a heavy task. It is also not clear how the system would resolve conflicts such as those arising when one feature would be better produced with one RP system but another would be better done on a different system. The main advantage of this approach would be that, if the features contained in the database were defined in the same way as those used by a specific CAD package, a direct link to that CAD package could be made. It is the authors opinion that this level of complexity is unnecessary to provide practical rapid prototyping advice to small companies.

Neither of the above systems has an automatic method of extracting object information directly from CAD data although both groups recognised that this would be a highly desirable feature.
3.2 System Requirements

In general, a successful computer based system for giving advice must fulfil several requirements [3]. In this case, the workings of the system should be as simple to operate and understand as possible. This includes how information is input into the system, how the system is controlled, and how the resulting advice is presented. Although chiefly designed for a target user, the system should be sufficiently clear to be used and understood by anyone.

User Input and Control

The input required by the system should be requested in a familiar format for the user. Unlike the systems described previously [1,2], it should not assume that the user has a detailed knowledge of materials properties or rapid prototyping technologies. The system should not require information which the user could not be expected to have readily at hand. In addition, the system should not be laborious to use. In particular, the user-input procedure especially should be kept to a minimum. The use and control of the system should be simple, intuitive and require minimal training.

The system should be constructed to tolerate errors or omissions in non-critical areas without any hindrance to the user. Where critical errors are made, the system should indicate not only the problem but the potential default values/limits, so enabling the user to continue using the system whilst helping to eliminate any similar errors in the future.

Processing

The system’s calculation time should be as quick as is reasonably possible, since the user is effectively idle whilst waiting for the advice. The total time spent obtaining the result should be much faster than existing methods of seeking similar advice, for example, communicating with an expert over the phone. However, for the purposes of this study processing time is not a high priority.
System Output

It is important that the advice provided should be concise, relevant and reliable. Like the input information, this advice should also be presented in a convenient and familiar format so that it can be readily assimilated into any existing tasks the user is undertaking. The resulting advice should therefore be presented using the same phrases, terminology and units as the user. If the user is to have a high degree of confidence in the resulting advice, the system should be able to indicate in simple, understandable terms, how or why a certain result is obtained. A brief rationale should be included with the initial advisory feedback, whilst a more detailed summary of the decision process should be available on request.

The design advice system should also express its results within acceptable limits. In reality, prototyping methods will vary in cost and lead-time depending upon the circumstances of the service provider and customer. Therefore, arriving at precise numerical data for cost and lead-times may be misleading. This system should aim to provide the user with enough information to select a viable route and seek a detailed quote from a service provider. The results of the system should be in the form of generalised “advice” or “guidance”, as opposed to definitive numerical data. Estimations for cost and lead time, based upon calculations that are essentially numerical, will obviously produce results as real numbers and in such cases these should be rounded to comply with the overall aims of the system.

Education

The system will aim to educate the user in both the subject area and in the actual system’s usage. With the objective of increasing users’ knowledge, the system should equip individuals with enough information to fully understand the resultant advice and to have confidence in the process.

Incorporating additional media (including descriptions, explanations, diagrams, photographs and references relating to that detailed in the resulting advice), may help
the user to accomplish this.

The system should enable the user to become sufficiently conversant in the subject area to discuss proposed prototyping routes with service providers. With continued use, the user should develop a sufficient perception of the results process to employ the system as a fast-check method; no longer needing to resort to the explanation material.

Access

Although it is not a priority in this investigation, commercial viability must be an issue for the target market. In computing terms, this will involve a consideration of computer types and operating systems. Cost will also be highly significant and the total cost of implementing the system should be well within the economic reach of the target users.

Updating

The system must be able to use the most up-to-date information possible, to provide the optimum advice. A commercially viable system must have in-built facilities allowing the information stored to be updated regularly, with the minimum effort and hindrance. Some of this information may be in a form that the user can control but some may need to be commanded by the system authors. During this study, the system will be in a constant state of construction and updating information is not a high priority.
3.3 Selection Criteria

Many factors have to be considered when selecting the optimum rapid prototyping process for the construction of a given component. These factors will be determined by the form of the object, the number of objects required, and the use for which the object is being created.

Most rapid prototyping systems are capable of producing models within certain limits. However when manufacturers state the limits of their machines they usually refer to the actual limits of the process technology and not necessarily to practical model building limits. Whilst a given RP system may be capable of producing a certain form it may not necessarily be practical or efficient. The difference between the effective limits and the theoretical limits are a matter of experience and this is where expert opinion will provide a more efficient selection than one based purely on the theoretical limits.

For example, Laminated Object Manufacturing is perfectly capable of creating parts with very thin walls. However, when the model has to be broken out from the waste material the weakness of the thin walls often leads to damage. Conversely Stereolithography is perfectly capable of creating parts with very thick sections but in practice this would prove excessively expensive. See Chapter 2.1: Rapid Prototyping Review.

When approaching the computer based selection of RP systems the limits have to be defined in terms the computer can handle. The limits of RP systems can usually be set as minima and maxima based on part features. For example, wall thickness, accuracy or layer thickness. The rapid prototyping systems can then be arranged according to these figures.

Of course for a given object different features may be better realised by different RP systems. Therefore it is important to prioritise these features. If this is the case the
most appropriate RP system would be selected according to the most important criteria. The highest priorities should be given to the criteria which show the greatest spread of RP system capabilities. If many RP processes are similarly capable in a certain respect then selection according to that respect would be of little practical use.

The first step in selecting an RP process must be to eliminate any processes which are not capable of meeting the desired criteria. Of those processes which remain, all will be capable of producing the desired result but some would prove more suitable than others. It would therefore make sense to use the most important criteria to eliminate processes and then sort through the remaining processes according to the next most important criteria and so on. When the processes have been sorted according to all of the important criteria, what remains may be considered a result. This may be a single process, a group of processes or no processes. Where one process remains this could be considered a recommendation. Where no processes remain the result may be considered as “RP not sufficiently capable”. Where a group of processes are all deemed capable of meeting the criteria other factors which are not necessarily a feature of the part may be considered.

If we consider the production of a single prototype component the criteria for selecting RP process could include the following: Layer thickness, minimum and maximum wall thickness, minimum feature size, accuracy, object size (compared to build envelope), mechanical strength of parts, build time and cost.

Of these factors some can be given priority over others. Unimportant factors include, for example, build envelope. Where the desired object is larger than the build envelope of a certain RP machine it a relatively simple matter to build the object in parts and assemble them. This may not be as satisfactory as a single build but does show that build volume is not an important factor in assessing the capability of RP systems. Maximum wall thickness is not applicable as a selection criteria as it is not really a theoretical limit. Any RP system can, if required, create objects a thick as its
build envelope. Of course in practice there are effective limits based upon economic considerations but these may be sorted after more critical features have been considered. Build time and cost are also not effective for sorting capability. An RP system may be perfectly capable of creating a given object but whether it is economically sound to do so is another matter. The layer thickness that RP systems build at tends to be similar and therefore it is not an important criteria for selection.

The most important factors here would therefore be *accuracy, minimum wall thickness* and *minimum feature size*. These factors are absolute limits determined by the process technology used to create the models. Minimum wall thickness and feature size equate to the same thing when considering the smallest drawing capability of RP processes. Therefore the most important selection criteria would be based upon the desired accuracy and minimum wall thickness of the object.

If only a very small number of prototypes are required the strength of the RP build material could be an important factor. This would have an effect on the RP process selection. However most RP process material properties are not comparable with production material properties, therefore it may not be possible to match these requirements. Even where rapid prototyping processes use production materials the deposition process will give different physical properties when compared to injection moulded parts. However more general properties may be specified such as “flexible” or “robust” and these may be used to select processes.

As soon as the number of prototypes required increases beyond a certain number the influence of these properties changes. For large parts it may be uneconomic to make more than one by rapid prototyping. However, for very small parts many may be built in one operation. It depends upon the size and shape of the parts in comparison to the build envelope of the machine. Over some time a rapid prototyping bureau can arrive at a general rule to determine the average size of parts and how many it is economic to build using rapid prototyping techniques.
As in nearly all cases it is uneconomic to make more than a few prototypes by RP processes secondary methods are used to create the prototypes from a single master pattern created by an RP process. When this is considered the physical properties of the RP process materials do not need to be matched against production materials. Of course there will still be physical demands according to the secondary tooling method for which the master pattern is used. So in these cases selection becomes a two stage process;

1) select an appropriate RP process to create the master pattern

2) select the most appropriate secondary tooling process to create the parts with the required physical properties.

The choice of the RP process used to produce the master pattern remains fixed by the object according to the highest priorities as identified above, accuracy and minimum wall thickness. All secondary tooling methods have an effective service life, that is the number of parts they can produce before the tool degrades below acceptable levels. Therefore the choice of secondary tooling process is mostly determined by the number of parts required. The physical properties of the materials used alters according to the secondary tooling process and this may also be considered a selection criteria.

A certain relationship exists between these considerations. Generally speaking as the number of parts a secondary tooling method can satisfactorily produce increases the closer the parts produced are to production items in terms of material and physical properties. The specification of physical properties is detailed in the following Chapter.

The selection process for the secondary tooling process now has two important criteria. The most important being the number required, with the prototype use category being a subset of that. The shape of the object will of course have some effect on the choice of secondary process but in these cases it is often a matter of adjusting or
adding to the process rather than eliminating it.

Because of the number related rule, based on tool life, different tooling methods can be arranged in a rank list. An initial selection can then be performed according to this rule. Subsequently, the selection can be tested against the next most important criterion and so on. If all of the criteria can be satisfied, a result is obtained. If at any point a criteria fails, the selection can simply move on to the next tooling method down the list.
3.4 Prototype Classification

It is relatively difficult to describe the intended use for which a prototype is being created. A list of all the possible tests a prototype could be required to perform would be enormous. To input a description of the intended tests would also be time consuming and would require sophisticated inference of the test description. This would be complex and would be a potential area for misunderstandings. The matter can be simplified by creating categories of prototype use. In a method, similar to that quoted in other texts relating to product development and rapid prototyping, the ‘Prototype Use’ defines the intended purpose of the prototype according to the physical demands required of it [1, 4, 5]. In approximate terms these groups range from purely visual models to “as manufactured” pre-production prototypes. The uses can be grouped as shown in Figure 3.4.1.

![Diagram of Prototype Use](image)

Figure 3.4.1. Grouping of Prototype Use.
Using these categories and the number of prototypes required, a basic tree can be constructed showing the various possible routes. Some rapid prototyping service providers also use similar categories when describing their capabilities and services to customers. In discussion with rapid prototyping experts this was agreed to be a suitable classification \([6, 7]\). These considerations are broadly similar to those described by S. O'Reilly and K. Denton \([8]\), with the exception that they suggested stipulating a budget and deadline before choosing a route.

For the purposes of this selection system, the prototype use is grouped into four categories. The physical requirements of the prototype will fall into one of the categories below. It may also be the case that the requirements of prototypes will pass through the different categories in turn as the development of the product nears production. This has reduced the possible inputs from a vast number of test descriptions to a choice of four categories. Each category could be sub-divided at a later date to allow more specific classifications.

a) Not Property Dependent

The use for which the prototype is intended does not depend on any specific physical properties. Such uses could include; scaled models, visual approval models, ergonomic test models, photographic or market research models and some non-functional fit and assembly tests.

b) Physical Property Dependent

This category applies to prototypes which are intended to prove some function that is dependent upon a certain physical property. For example, testing a snap fit for an assembly test requires a material with a similar flexural modulus as the intended production material. The prototype material does not have to be the production material but merely approximate it with regard to the physical property in question. For example, in many cases the key design consideration will be stiffness and for many plastics there will be a polyurethane resin suitable for vacuum casting or RIM
moulding which closely approximates the required stiffness.

c) Production Material Dependent

There are some tests which will require the same material as that intended for production. These may include, for example, friction tests, creep tests or performance tests over specific temperature ranges. Other considerations may be more concerned with dielectric or chemical properties, such as resistance to solvents. In these cases there may not be another convenient material which displays the required property or combination of properties and the production material will have to be used. However, the part may not necessarily need to be formed in exactly the same manner as is intended for volume manufacture.

d) Production Process Dependent

As an extension of the previous group prototypes in this category will be required to be as close to production parts as possible and this may require using exactly the same production process. Tests in this category may include; stress analysis, reliability tests, fatigue or aging tests. For example, in the production of plastic parts the flow of the molten material in the mould may have an important effect on the strength of the part. Similarly when amorphous plastic properties are called for, the moulding process is critical. If the plastic is not injected under sufficient pressure and chilled rapidly, the resultant plastic will show a crystalline structure. In these cases the production material and process must be used. It may also be the case that the production process as a whole is itself being trial run.
3.5 System Structure

The rules governing the system can be made up of basic IF, THEN, ELSE style conditional statements which are used to test limits on certain criteria. The basic selection rule structure is based upon prioritised criteria being tested against limits associated with processes. The processes are arranged sequentially according to the limits of the most important criteria. The most important criteria are tested against these limits until they are satisfied. If they are satisfied the selection will test a set of further criteria against limits associated with the initial selection. If any of these fail the selection fails and the next process in the sequence is tested.

Usually in expert systems the processes would not be arranged in a specific order. Moving between the processes would be controlled by a separate interpreter [9]. In this case because there is a single most important criteria the processes can be given an order. If a condition in a given process is not satisfied the selection will move on to the next process in the order. However when certain conditions are not satisfied the process may merely require modification rather than failing. In these cases the selection will move on to other areas to implement the modifications to the process.

This method of arranging processes has distinct advantages, mainly simplicity of construction and speed. The selection will work faster because it only searches one way. If at any point a process fails the selection criteria the system does not need to search the whole list of processes from the beginning again, but simply move on to the next process.

Example

Processes to be selected are arranged into a rank list according to the most important criteria $C_1$, a real number. The second most important criteria is a category $C_2$, also arranged in order. To arrive at the selection the input $C_1$ is used to move down the rank list of processes until it is satisfied. Upon this initial selection the next most important criteria, $C_2$, is tested for the selected process. If it is also satisfied then
that process is selected and a result is obtained, if not the selection will move down the list to the next process. Because of the rank list there is no need to test C1 again and therefore only C2 needs to be tested.

<table>
<thead>
<tr>
<th>Process Sequence</th>
<th>Input</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>Input 1</td>
<td>Process 2</td>
</tr>
<tr>
<td>C1≤10</td>
<td>C1=20</td>
<td></td>
</tr>
<tr>
<td>C2=A</td>
<td>C2=A</td>
<td></td>
</tr>
<tr>
<td>Process 2</td>
<td>Input 2</td>
<td>Process 2</td>
</tr>
<tr>
<td>C1≤20</td>
<td>C1=5</td>
<td></td>
</tr>
<tr>
<td>C2=A and B</td>
<td>C2=B</td>
<td></td>
</tr>
<tr>
<td>Process 3</td>
<td>Input 3</td>
<td>Process 3</td>
</tr>
<tr>
<td>C1≤50</td>
<td>C1=30</td>
<td></td>
</tr>
<tr>
<td>C2=A and B</td>
<td>C2=B</td>
<td></td>
</tr>
<tr>
<td>Process 4</td>
<td>Input 4</td>
<td>Process 4</td>
</tr>
<tr>
<td>C1≤100</td>
<td>C1=70</td>
<td></td>
</tr>
<tr>
<td>C2=A, B and C</td>
<td>C2=A</td>
<td></td>
</tr>
<tr>
<td>Process 5</td>
<td>C1≤200</td>
<td></td>
</tr>
<tr>
<td>C2=A, B, C, and D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Input 1 the first criteria, C1, is greater than 10. Therefore Process 1 is not selected and the system moves on to the next process in the rank list. For Process 2 criteria C1 is equal to 20 and therefore it is initially selected. The second most important criteria, C2, is now considered. The categories are both A therefore the C2 is also satisfied and a final selection can be made.
Of course this will only work where the most important criteria can be arranged into a rank list according to a greater than or less than test or using set theory, but where it will work it is a very simple and fast means of selecting multiple criteria processes.

Process Subroutine Structure

In the process subroutines there are basically two types of rule:

a) decision rules
b) calculation rules

The decision rules use the input data to select possible methods for a solution. These will often be in the form of either IF, THEN, ELSE statements or Case Statements. The calculation rules will perform calculations to create the results of the system. These will often be mathematical in nature. The input data consists of manually input data and inferred data. The manually input data is in the form of real numbers, integers and selections from pick lists. These will define the users requirements for the prototype part. The other data consists of an object description. This data is inferred or calculated from the object in question.

The result of the system is a Rapid Prototyping & Tooling (RP&T) “method”. This method will be a collection of activities that will enable the production of the required number of prototypes with the required physical properties. Each RP&T method will have a limit on the number of parts it can reliably produce. If each method has a rule or subroutine written for it they can be assembled in order of increasing production limit into a rank list as described above. This limit can be directly compared to the user input “Number of parts required”. Therefore the first rule encountered in the system will move down the list of subroutines until it reaches the first subroutine that satisfies the number required.

Another important requisite of the method will be whether the physical properties of the parts produced by this method will satisfy the users specification. To
simplify matters this is defined by a list of categories from which the user selects one. There is a relationship between the number of parts a particular tooling process is capable of producing and the physical properties of the parts they produce. As the process approaches volume production methods and capabilities the number of parts possible increases. Therefore the subroutines for the methods can be grouped into the categories whilst still being listed overall in order of increasing number possible. Thus a second sorting rule can use this selected category to “jump” down the list until it meets a method capable of producing parts with the required physical properties.

If no physical properties are specified by the user the initial selection will be governed solely by the “Number of parts required”. If a physical property is defined by picking the appropriate category the selection will be performed firstly on the “Number of parts required”. This initial selection will then be checked against which category of physical properties it can produce. If this is correct the selection takes place, if not the system will jump down the list until the condition is satisfied. This is the most basic rule in the system and can be seen in schematic form in Figure 3.5.1. The basic structure of the code is indicated in Figure 3.5.2.

![Figure 3.5.1. Basic Rule Structure.](image-url)
Limit Checking Rules  
check for erroneous input data

First Selection Rule

Second Selection Rule  
performs initial selection

etc...

Tooling Method 1 Subroutine
1) Check rules  
accept or reject this method
2) Implementation rules  
implement this method
3) Calculation rules  
perform calculations of results

Tooling Method 2 Subroutine
1) Check rules  
accept or reject this method
2) Implementation rules  
implement this method
3) Calculation rules  
perform calculations of results

etc.

Figure 3.5.2. Basic Code Structure.

Once a method (subroutine) has been initially selected other rules within that subroutine will then check whether the other aspects of the input data can be satisfied by the selected method. These rules will decide whether the method will be:

a) capable. If not the system will jump to the next subroutine.

b) suitable. If it is capable what additional processes (if necessary) will be required to use the method successfully. Are there other, more suitable alternatives?

If all of the input data is satisfied the subroutine will follow another set of rules which will calculate and display the resulting advice, the costs and lead times and prepare the explanation material.

The methods for producing significant numbers of prototype parts are most often secondary tooling processes which use rapid prototyping (RP) to provide the necessary master pattern. While the secondary tooling method is being selected other rules will be running to select which RP method would be best suited to the
production of the original master pattern. This may often be done independently of the secondary tooling decisions although there may be some cases where these two sets of rules affect each other.

For example, the selection of Selective Laser Sintered tools. These are built directly on RP machines and therefore no master pattern is required. The rules may still select the best method for producing a master pattern but the subsequent tooling method could either eliminate it or adjust the results to indicate that, although possible, it is not necessary to produce a master pattern.

Selection of the most suitable RP method will identify characteristics of the object and use them initially to eliminate the methods which are not capable of producing the required results. Of the remaining methods some may be unsuitable and these too will be selected out. Rather than iterating until only one method remains, if a number of methods are all equally suitable (within limits) they will all be displayed and their relative merits described in the explanation material. The user can then make an informed decision of which method to choose based on the explanation.

As before, some of these rules will be more important than others. For example "producible wall thickness" will be crucial in selecting an appropriate method. Equally important may be accuracy. However, build size constraints are less important. If a part is too big for the RP machine it can simply be built in parts and assembled. The rules in that situation would just adjust the method to account for the separate builds and the assembly. As before once the method is established other rules calculate the results, costs, lead times and prepare the explanation material.

The explanation material should contain descriptions of the processes and what is involved in their implementation including, where appropriate, diagrams, photographs and references.
3.6 References


6) Freeman, P., 1995 to 1998. Private communication. DERCRP Unit, Cardiff UK.


4.1 Potential Software Solutions

Initially several different software solutions were evaluated to find a suitable method for constructing a computer based rapid prototyping design advice system. It was anticipated that the system would be constructed in a software environment that would access CAD data and allow the user to input their requirements and after processing the results, display them to the user. This is shown schematically in Figure 4.1.1.

Although the evaluation criteria includes ease of use for the intended end user, the main consideration involved balancing technical requirements with ease and speed of system construction and development. There follows a description of some of the approaches evaluated, stating some of their advantages and disadvantages.

![Diagram of user interaction]
4.2 Multimedia Authoring Software

Object oriented multimedia authoring software allows the rapid construction of computer programs. They are usually in the form of an application based on a stacked card metaphor which is controlled by program code attached to elements of the application. Once completed they often require another piece of software to "play" them. Examples include, MetaCard, ToolBook and SuperCard. MetaCard is available for UNIX and PC/Windows operating systems and ToolBook runs under the PC/Windows operating system. SuperCard operates on Apple Macintosh computers and is similar to the pioneer of this type of software, the Apple application HyperCard. These applications are often used to create on-line tutorial and help programs as well as other multimedia applications. This type of application makes use of a series of screens, or cards, containing graphics, text, buttons and fields. These cards are controlled by object oriented programs, sometimes referred to as scripts.

The advantages of using this type of authoring software include the simplicity of the programming which controls the system and the ease of creating graphical user interfaces. Fields, buttons, graphics, text, even sounds and video are all easily created and controlled. This kind of software is also very flexible. With respect to this study, a limiting factor is the difficulty of directly importing binary Computer Aided Design (CAD) data. Another problem is the limited script length available. For example, SuperCard cannot read or write binary files but can read and write text files. In addition, the script length limit makes it necessary to split the scripts which can be inconvenient.

This type of software is also not usually capable of high level mathematical functions although they can often access other external applications and files, such as spreadsheets and databases. These applications are obviously intended to be used for the production of multimedia programs and have no in built facility for incorporating a knowledge base or the rules with which to control selection procedures.
To evaluate this approach a trial script was created for the selection system using SuperCard, shown schematically in Figure 4.2.1. The script worked by cascading down through sequential subroutines until all of the input parameters are satisfied in the manner described in Chapter 3.5: System Structure.

The script works by having a subroutine for each possible prototyping route and arranging the routes in a specific order. The subroutine will output the different prototyping routes according to prioritised rules which will govern whether or not to move on to the next possible route. However, this means that alternative routes are not compared directly during a single solution. The first and most important rule is concerned with the number of prototypes required. Other rules act as interrupts which jump into the cascade at different levels. For example, the ‘Prototype Use’ classification described above will jump into the cascade at different levels. This can be seen in schematic representation shown in Figure 4.2.2.

Figure 4.2.1. Schematic of the system using Multimedia Authoring Software.
Other rules based within the subroutines will reject the method and move on to the next level if certain process specific rules are contravened. This system will give a single result for a single set of inputs. Detailed explanations of the processes described in the results can be accessed using 'Help' windows. These include text, diagrams and photographs. The incorporation of these visual aids is simple and effective using this kind of software.

The result of the evaluation was a system which operated well with the limited information put into it and had a satisfactory user interface. No attempt was made at this stage to obtain an object description automatically. Instead the key characteristics of the object were manually entered into the relevant fields \[1, 2\].

Figure 4.2.2. Basic Rule Structure.
4.3 Industrial Costing Analysis Software

The principal reason for evaluating this software, called ‘Cost Advantage’, is that it is an “off the shelf” knowledge based system with an optional direct connection to specific three dimensional CAD systems. It has dedicated facilities for incorporating manufacturing process knowledge, rules and restrictions but is intended for the analysis of a component or assembly to give a breakdown of manufacturing costs.

It was hoped that this piece of software could be customised to meet the requirements of this study. However, the user interface cannot be edited and is not intended to guide a user through a series of sequential decisions. This made the alteration of this software to obtain the user interface and results output required for this study extremely difficult.

The main problems arise from the fact that the hierarchical structure used by the software can only be reduced to three trees, called Process, Material and Feature. Picking items from these three trees gives a ‘context’. The system will then analyse this context and output a costing breakdown according to the rules within the cost model. The results also can only be shown as three columns of costs relating to Process, Material and Tooling. These do not tie in with the requirements of the RP selection system. Although the titles of these output columns can be changed they cannot be deleted or added to. This makes the output of a process recommendation in a text form impossible. Even the output of numerical data for cost and time is limited to these three types.

To evaluate this piece of software a limited selection system was created, shown schematically in Figure 4.2.1. However, using the selection structure described previously was not possible. Instead the three basic hierarchical trees in Cost Advantage were set up as lists of choices for ‘RP Processes’, ‘Number of Prototypes Required’ and ‘Prototype Use’. Selecting different categories of ‘Prototype Use’ excluded some of the secondary tooling routes which relate to the ‘Number of Prototypes
Required'. Information about the object is input as Process characteristics. The RP Processes and Secondary tooling routes also have rules attached to them to warn of limitations. See Figure 4.3.2.

Figure 4.3.1. Schematic of system using Industrial Costing Analysis Software.

Figure 4.3.2. Cost Advantage Window.
Hence, rather than recommending a tooling route the system simply excludes what is not suitable until only a few possibilities remain. These few remaining possibilities can then be selected and each one analysed in turn by the user. This allows comparisons to be made and recorded but does mean that the user may be presented with a choice of RP processes and prototyping routes about which they may have little knowledge.

The fact that no priority can be assigned to the trees presents a major problem. The items from the three trees can be picked in any order. Because of this if there are too many exclusions across the three trees for a given ‘context’ it is possible that the system can get ‘trapped’. Consequently, not only is the user unable to make the selection they require, but the software hangs requiring the program to be shut down and restarted.

It is possible to attach explanation windows containing text to any area of the system. Graphics, in the form of bit maps, can also be included in separate windows. However, the layout and visual appearance of the system remains fixed.

Ideally the dynamic link to the three dimensional CAD application, in this case SDRC I-DEAS, would have been tested. However, the code available at the time of evaluation did not allow for this linking. However, even if it had been available the object information that could have been accessed would still have been limited to parametric dimensions which are selected by the user and linked to Cost Advantage. In this respect Cost Advantage acts as a spreadsheet and the parametric dimensions are passed from the CAD application as numerical variables. Chapter 5.2 : Dynamic Linking to 3D CAD Applications, discusses the general problems associated with dynamic linking to CAD systems in greater detail [3].
4.4 Mathematical Analysis Software

The use of a mathematical analysis package, such as Matlab, allows complex mathematical calculations and operations to be performed. Functions in Matlab are controlled by programs written in its own language. This kind of software can be very flexible and powerful, for example Matlab can read and write both binary and text files and also has the capability of constructing graphical user interfaces. Matlab can also be used to create the rules and calculations necessary for the estimation of cost and lead time. It is therefore possible to construct a selection system using Matlab despite it having no in built facility for knowledge based operations.

Although Matlab cannot be dynamically linked to three dimensional computer aided design (CAD) software it can, unlike multimedia authoring software, read and write binary and text files. Therefore if, for example, a generic binary CAD output data file is used as the object description it is possible to write routines in Matlab to read in, visualise and manipulate the object data. Once the file had been read in, routines could also be written to derive information about the object such as size, surface area and volume. Such a system is shown schematically in Figure 4.4.1.

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**Figure 4.4.1.** Schematic of system using Mathematical Analysis Software.

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In addition, depending on the CAD data format, it may be possible to write more complex routines which can isolate and identify specific features of the object. This would give a greater degree of automation to the selection procedure and minimise the manual input of data regarding the size and shape of the object without experiencing any of the problems associated with directly linking to a CAD system.

Using Matlab allows the use of complex mathematical functions that would be difficult to achieve using multimedia authoring software yet it also has graphical user interface tools built into it. However, the sophistication and manipulation of the graphical user interface would better achieved using multimedia authoring software, such as SuperCard. The programming language of Matlab is, in the author’s opinion, more difficult to learn than, for example, the scripting language of SuperCard.

In short, the graphical interface tools and binary file capability combined with the flexibility of the programming environment make Matlab a viable option for the creation of a selection system that fulfils the requirements of this study [4].
4.5 Conclusion

After experimenting with the various software packages described in this chapter, it was established that, when compared to the alternative approaches, attempting to customise Cost Advantage would not be the most satisfactory approach for this study. Firstly, the desired user interface could not be created in a reliable format. Secondly, although it remained untested, the dynamic CAD link would not automatically provide sufficient descriptive information regarding the component in question. The environment for designing decision rules, and more importantly, structure proved to be too restrictive to allow for a wide variety of solutions to be investigated.

In contrast SuperCard proved to be very flexible and a limited working system with a satisfactory graphical user interface was quickly created. The major drawbacks of this approach being the inability to read in binary files and perform complex mathematical operations.

Matlab also proved flexible and operations involving complex mathematical calculations were easily handled. The fact that binary files can be read in is another major advantage. However the definition of text based properties is more complex and time consuming when compared to SuperCard. Similarly, constructing graphical user interfaces is simpler, quicker and more sophisticated using SuperCard. When graphical user interfaces were created with Matlab they were observed to operate much slower than similar interfaces created using SuperCard.
4.6 Additional Considerations

When assessing these software applications for use in this study some other considerations were noted. Although these were not of principal importance to the research they may be worth reporting when considering the aim of the project (as stated in Chapter 1) is a system targeted towards the needs to small companies with limited resources. Clearly, it would be highly beneficial if the prototype system created as a result of this research could be in a format available and familiar to the target user.

For example, Cost Advantage only operates under UNIX operating systems. Therefore, using Cost Advantage would have required the purchase of an expensive UNIX work station. In addition, even for educational use, the software itself was likely to cost as much as £4000. This type of software and platform is unlikely to prove widely accessible to SMEs.

In comparison the object oriented authoring software evaluated, SuperCard, is available for several hundred pounds and operates under the Apple Macintosh operating system. Likewise, similar applications are available at comparable cost which operate under UNIX and more importantly PC/Windows operating systems. An educational version of Matlab, costing less than £40, is available for UNIX, PC/Windows or Macintosh operating systems. Using any of these applications would only require the use of a reasonably well specified PC or Macintosh computer. Therefore these approaches are more likely to be accessible to SMEs.
4.7 References


5.1 Obtaining an Object Description

A desirable feature of a computer-based system would be the incorporation of an automatic object description. The information can be obtained, either directly or indirectly, from three dimensional Computer Aided Design (CAD) applications. Access to the required information could be achieved in a number of ways and there are advantages and problems associated with each approach. For the selection system, information about the overall size, volume, surface area, wall thickness and feature sizes is required. A successful approach should allow all of the required object information to be accurately and rapidly entered into the selection system in one automated step.

5.2 Dynamic Linking to 3D CAD Applications

The selection system could be directly linked to a CAD application. There are facilities in many CAD applications which can transfer data to spreadsheets. Such methods may be used to control parametric variables or for evaluating costings and manufacturability of parts designed using the CAD application. These links usually operate by passing parametric (numerical) values, usually dimensions, to a spreadsheet. These links may be dynamic, meaning values changed in the CAD environment will automatically update the spreadsheet and vice versa. Calculations are performed within the spreadsheet to arrive at the desired results.

However, when this was attempted using a three-dimensional CAD system, (in this case I-DEAS Master Series from SDRC), problems were encountered. These problems stem from the fact that the information required for the selection system was difficult to extract from the CAD application in a satisfactory manner. Some of the items required could be accessed but others could not. Even with respect to the items that could be accessed by the CAD operator, there was no convenient method of extracting them in one operation or of putting them into a single output format.

For example, due to the manner in which the CAD modeller defines geometric
features and shapes, it would be very difficult to ascertain the minimum wall thickness of an object. To accomplish this would require a searching algorithm to be written which could analyse a CAD object and calculate the minimum wall thickness. This would require access to, and understanding of, the CAD application coding and operation. Even if such an algorithm was created, it would require considerable processing time and would only be applicable to that particular CAD system.

In brief:

- The CAD system can report the Volume
- The CAD system does not report the other statistics required for this study
- The Extents cannot be accessed easily
- The Smallest Design Feature does not always equate to smallest CAD feature. For example, a large and complex curved surface patch would be defined as a single CAD feature.
- A searching algorithm would need to be developed to find wall thicknesses.

SDRC will not give full third party access to the I-DEAS code and its software structure. Its ‘Open-Link’ will only give a superficial link between selected parametric dimensions and an external spreadsheet [1].

The conclusion was that there was, unfortunately, no possible way of extracting all of the required information in a single automated operation. To embark on producing software capable of overcoming these problems would have required the full co-operation of the CAD developer and taken many months. This would not have been a time-efficient method of obtaining, what is essentially, simple data.

A further disadvantage of linking to a specific CAD application is that the resulting system is then limited to operating only with that particular CAD system. A further problem is that it might also restrict potential users of the design advice system to CAD operators. The person responsible for investigating or planning the
prototyping stage of product development is not necessarily a CAD operator. For these reasons, it was felt that this approach was not the most satisfactory approach to the development of a design advice system for the target users of this study.

Such an approach would, perhaps, be better suited to a large company, such as those in the aerospace or automotive sectors, where CAD applications and practices are standardised. Such an organisation would have the financial and manpower resources necessary to implement an integrated CAD/design advice system. The advantage of their situation being, that a larger company would have a greater bargaining power with the CAD vendors; thus ensuring their co-operation with the company in question.
5.3 Using a Neutral File Format

Instead of using a direct link to a three dimensional CAD package, the object description could come from a neutral file format used as a transfer between different computer applications (both CAD and CAM). This method would however, not be a dynamic link. Values altered in the selection system would not affect the CAD model. Also, for every modification to the CAD model, a new transfer file would need to be generated.

Incompatible data formats can lead to frustrating and significant delays in product development and care should be taken where possible to avoid these problems [2]. However, one of the main advantages of using a neutral file format is the universal nature of the information, since this would allow similar access to data from a wide range of CAD systems. The data is also portable, allowing the selection system software to be remote from the CAD application which may prove to be a distinct advantage. The method of defining the geometry may also allow the required information to be accessed more simply in comparison to the CAD application that created it. As the neutral file format describes the whole object it can be analysed using algorithms, which may be able to isolate and identify the required properties. There are several neutral file formats available for the transfer of three-dimensional computer data. Examples of commonly used formats include; IGES, VDA/FS, STEP, NCC code, DXF and STL.

IGES, (Initial Graphics Exchange Specification), is the oldest format for the transfer of CAD data. An IGES file can be in either text or binary format and consists of a basic list of geometric features from which the CAD application can construct the model. IGES Version 1 was the first recognised international standard file format for the transfer of CAD data and covered 34 geometric entities. Later, Version 3 was accepted as an international standard and supported 50 geometric entities. At that time, IGES could only support cubic surfaces. Later, in Version 5, solid information in the form of alternate boundary representation (B-rep) was included.
Due to the way the file is constructed, it would be relatively simple to retrieve information relating to the size of certain geometric features, such as arcs and radii. Using the co-ordinates, overall object sizes could also be derived. However, unless the IGES file was of the latest version, including B-rep solid information, it would be difficult to obtain information such as surface area and volume. To derive this information would require different algorithms for each type of geometric solid. Effectively, the model would have to be rebuilt using the information in the IGES file.

To isolate information such as minimum wall thickness would prove difficult. Other more general problems associated with the IGES format stem from the large number of versions (both standard and 'flavoured') for specific CAD applications. Some CAD applications use features that cannot be well represented by IGES and information relating to them may be lost [3]. Figure 5.3.1 shows the start and end of a typical IGES file [4, 5].

![Figure 5.3.1. Start and end of a typical IGES file.](image-url)
DXF (Data Exchange File) is a file format created by Autodesk Inc. for use with its highly popular AutoCAD CAD package [6]. The file consists of a verbose list of line entities. This file format is intended for use with AutoDesk products and software written specifically to work with them. It is also more commonly used for two-dimensional CAD data but has recently been upgraded (in line with their CAD applications) to include solids information (in the form of the ACIS kernel). Calculating properties such as volume and surface area would require translators for effective reconstruction of the CAD model from the DXF file. Therefore, isolating features such as minimum wall thickness would be highly complex and time consuming.

STEP (Standard for Exchange of Product Data) is a more recent file format, designed to provide a sophisticated level of data transfer between different CAD applications [7]. Unlike IGES, it contains a record of geometric and form features, topology, dimensions and tolerances as well as the ability to suppress them from the model if required. STEP uses a language called Express to define entities and describe the properties of the entity. However, it is not currently in universal usage in the UK. The high level of information available from the STEP file format does provide opportunities for calculating properties such as volume and surface area, but this would involve writing translators that could reconstruct the model from the Express entities. However, isolating features such as minimum wall thickness would be as complex an issue as attempting to isolate them from the CAD model.

The Express definition structure for a point might be:

```plaintext
ENTITY point;
x_coordinate:real;
y_coordinate:real;
z_coordinate:real;
END_ENTITY
```
Actual instances of these on the physical file could be as follows:

\[
\text{V15 = POINT (3.3, 4.4, 5.5);}
\]

\[
\text{V16 = POINT (6.6, 7.7, 8.8);}
\]

**VDA/FS** (Verband der AutombilindustrieFlaechenschnittstelle) is a threedimensional translation format which is often used in the automotive industry. It was created as a standard in Germany, primarily for the transfer of higher order surfaces which were, at the time, not possible with IGES. Problems involved in using this format are similar to those encountered when trying to isolate the required information from IGES files. It is not often used outside the automotive industry [8].

**CNC** (Computer Numerical Control) code, normally used for computer controlled machining, is a relatively simple format consisting of a list of coordinate paths separated by commands relating to machining parameters [3]. Usually, these paths are outside the object boundary and are used as cutter paths. However, they can also be used to define paths inside the object boundary. For example, Fused Deposition Modelling uses paths similar to CNC code to control the extrusion head which creates the layers of models built using this RP process.

Using this kind of information, various simple properties can be isolated (e.g. size and extents). It is also relatively simple to create the data in a layered format, which would simulate the slicing of the models used in rapid prototyping. Properties relating to the layer contour data could also be isolated.

Most CAD applications use standard NC code translators to produce cutter paths for machining. To successfully implement this kind of approach, we would need to integrate translators to produce NC code relating to the internal contours of the object from the CAD environment or, alternatively, translate external path data to internal object path data. This would be time-consuming and may have to be repeated for different CAD applications.
STL (Stereolithography) is a very simple file format originally created for use with stereolithography rapid prototyping equipment [3, 9]. The file consists of a list of triangular facets which approximate the surface of the CAD model. Each facet also has a normal, indicating the outer surface of the CAD model. These files are sliced to produce the contour data used by rapid prototyping machines to produce layered models. The simple geometry used in the object definition allows the straightforward slicing of the file to produce the contour data used by the RP machines. The simplicity of the file allows mathematical isolation of properties such as size, surface area and volume to be calculated using relatively simple geometric formulae. The format allows the whole object to be sliced with a single, simple algorithm. Once sliced properties associated with the slice data also can be isolated.

In comparison to other neutral file formats, this may be a major advantage when attempting to estimate build times for various rapid-prototyping processes. Another major advantage is the convenience of using exactly the same file with the design advice system and any consequent rapid prototyping processes, thus saving time and eliminating additional translation stages and any possible discrepancies which may arise from them.

The file format is now considered a de-facto industry standard for use in all rapid prototyping processes and is in widespread use. The STL file format is described in more detail in the next Chapter.

VRML (Virtual Reality Modelling Language) is a three-dimensional representation of objects specifically written for use on the Internet [10]. It is a triangular-faceted surface approximation, very similar to the STL file format. Many CAD packages can export these files and there are several viewing programs written for the internet which allow manipulation of the object. This similarity means that many of the advantages of using the STL file format also apply to VRML. In addition, the automatic internet capability is another advantage.
Conclusion

Of the available neutral file formats, the STL file is the most compatible with the selection system, for the following reasons:

- It was specifically created for use with Rapid Prototyping processes
- Almost all three dimensional CAD systems can output an STL file
- It can be used as the input data to all of the currently available RP machines
- Mathematically simple format greatly reduces the number of different interrogation algorithms required to derive object information and slicing.

Due to the wide availability of the STL file output capability and the simplicity of the format, it is the most appropriate approach to obtaining the object description information required for this selection system. There would be no concerns about translation error between the object description used by the selection system and that used in the eventual rapid prototyping, since the same file would be used for both. The availability of binary files allows them to be read at a faster rate and minimises storage requirements.

For these reasons it was decided to attempt reading and interrogating the STL file format for the information required by the design advice system.
5.4 The STL File Format

The STL file format was created by 3D Systems Inc as a representation of models created using three-dimensional CAD applications. The file is used as the input to their stereolithography rapid prototyping systems, hence the STL suffix. It has since become a standard transfer file for every rapid prototyping system from all of the common three dimensional CAD systems.

The three-dimensional CAD model is approximated by a triangular-faceted surface. The STL file is then generated as a list of triangles in either binary or text format. The data for each triangle consists of the co-ordinates of the vertices and a facet-normal which indicates the outside surface. Therefore, the higher the resolution, the larger the number of small triangles and the greater the STL file size.

Figure 5.4.1 shows the start and end of an STL file in text format. The file simply describes the triangles which make up a three-dimensional model. The first line describes the direction of the facet-normal. This shows which is the outside surface of the facet. The next three lines give the co-ordinates of the three vertices of the facet.

```
solid FILENAME
  facet normal 1.0000000e+00 0.0000000e+00 0.0000000e+00
  outer loop
    vertex 0.0000000e+00 -1.204845e+00 -1.658504e+00
    vertex 0.0000000e+00 -1.235913e+00 -3.804270e+00
    vertex 0.0000000e+00 0.0000000e+00 -4.000000e+00
  endloop
endfacet
facet normal 0.0000000e+00 1.564194e-01 9.876907e-01
  outer loop
    vertex 1.0000000e+00 0.0000000e+00 -4.0000000e+00
    vertex 0.0000000e+00 0.0000000e+00 -4.0000000e+00
    vertex 0.0000000e+00 -1.235913e+00 -3.804270e+00
  endloop
endfacet
and so on...
facet normal 1.0000000e+00 0.0000000e+00 0.0000000e+00
  outer loop
    vertex 1.0000000e+00 4.000088e+00 1.221134e+04
    vertex 1.0000000e+00 3.535500e+00 3.535500e+00
    vertex 1.0000000e+00 3.999953e+00 0.0000000e+00
  endloop
endfacet
endsolid FILENAME
```

Figure 5.4.1. The start and end of an STL file in text format.

The nature of the file makes the slicing, necessary for RP a relatively simple mathematical procedure. This simplicity also makes scaling and translation of STL
files a straightforward matter. There are also applications available which segment STL files and close off the resulting open side. These also allow the angle of faces to be identified and this is a necessary feature for stereolithography.

For a rapid prototype build to be successful, the STL file should have no gaps between facets and all the facets should have their normals facing the outside of the part. Small problems in the file can be corrected with software. Solid modelling CAD systems rarely have problems creating STL files but surface modellers can pose problems if all the surfaces are not properly attached and trimmed. The STL file must form one enclosed volume. The gaps represent problems when they coincide with the level at which a slice is being taken, leading to gaps in the boundary of the layer.

When the CAD system creates the STL file it will apply a resolution to the file. This is normally achieved by the CAD user specifying an absolute maximum deviation. This is normally expressed in the units being used, typically 0.01mm. The deviation is the perpendicular distance between a facet and the original CAD data where the facet forms a chord at a curved surface. See Figure 5.4.2.

![Figure 5.4.2. Facet Deviation.](image)

In essence, a smaller deviation will give a more accurate representation of the CAD model. However, as the STL file is essentially a list of triangles the file size is
directly proportional to the number of facets. Therefore, decreasing the maximum deviation results in an STL file with a greater number of smaller facets giving a larger file. See Figure 5.4.3.

![Figure 5.4.3. Effect of altering facet deviation.](image)

The deviation is sometimes expressed as a percentage of chord length as shown in Figure 5.4.4 below.

![Figure 5.4.4. Maximum deviation expressed as a percentage of chord length.](image)

Maximum deviation = perpendicular deviation / chord length * 100
5.5 Interrogating the STL File Format

Using Matlab, a program was written that would read in a binary STL file and put the data into a matrix format. This matrix data can then be used to generate a three-dimensional shaded image of the STL file, as shown in Figure 5.5.1.

![Shaded image of an STL file.](image)

Figure 5.5.1. Shaded image of an STL file.

Once the data is in matrix form and the format is known, three-dimensional geometry can be used to obtain properties of the faceted model. The most basic property of the model to be calculated is the extents of the model, indicating its overall dimensions. From this, the centre of the extents can easily be found. These coordinates may be useful for further model transformations, like rotations. In addition, the total surface area can be found by calculating and summing the area of each triangular facet.

The volume can be calculated by creating a tetrahedron from each triangular facet using the origin as the fourth vertex. The volumes of all the tetrahedrons can then be added together. If the sign of the resulting volume of each tetrahedron is taken into consideration when all the volumes are added, the volumes of triangles facing the origin are effectively subtracted, leaving the total as the volume of the model.
Additional routines were written that could slice through the object at a certain height (in the z axis). Certain properties relating to the slice could then be calculated. These include, for example, the cross sectional area and perimeter of the slice. If slices are taken at different heights through the object, more assumptions can be made about its overall shape. As most rapid prototyping processes basically work by depositing layers in a certain manner, these slice properties can be used as a sound basis for the estimation of rapid prototyping build times and therefore, costs.

The more slices that are taken, the greater the estimation accuracy but the processing time of the selection system would increase accordingly and a compromise has to be made. As objects vary in height, the routine written would slice the object at percentage levels of its height. In this case, the routines sliced at five heights; 1%, 25%, 50%, 75% and 99% of the maximum height in the z axis. The information derived from the interrogation of each slice was also stored in a matrix format.

These routines were trialled individually and, when found to be reliable, were assembled into a command routine and sub-routines, shown schematically in Figure 5.5.2. This means that with one instruction, all of the functions would be performed. The results of the calculation were then written into a text file for use externally of Matlab. Other programs, SuperCard, for example, can read in such text files. The full Matlab code for all of the routines is given in Appendices 4, 5 and 6.
Figure 5.5.2. Schematic of Matlab routines.
5.6 Result of the Evaluation

The problems associated with direct linking to a specific three dimensional CAD package meant that utilising a neutral file format for the object description proved the more advantageous and versatile approach. Therefore, it became clear that this would be the preferred method. Of the neutral file formats available, the mathematical simplicity and widespread use of the STL file format suggested it would be the most suitable for the purposes of this study.

Based on the limitations of the possible approaches investigated, it is clear that a solution based on a combination of SuperCard and Matlab could successfully exploit the positive advantages of both applications whilst simultaneously overcoming their respective shortfalls.

The key reason for using Matlab was its ability to read in and extract relevant information from the binary STL file format. This is something which is not easily achieved with the alternative methods investigated. This factor, when combined with SuperCard’s ability to create a flexible graphical user-interface means that the whole system could be constructed as long as the two applications are able to communicate with each other. Another major advantage of this approach being the fact that the investigative work conducted on both SuperCard and Matlab could be further developed rather than discarded saving a great deal of valuable development time.
5.7 References


7) STEP Standard, ISO 10303, International Organisation for Standardisation (ISO). 1, Rue de Varembé, Case postale 56, CH-1211 Genève 20, Switzerland


http://www.vrml.org/VRML2.0/FINAL/spec/index.html
6.1 Development of the Graphical User Interface

Aims

When considering the target user of this computer based design advice system it is vital that the user interface should be simple and intuitive. As the system is not necessarily aimed at highly computer literate users, engineers or scientists, it should not require any special training or computer knowledge to successfully run a solution. Likewise, the specification of precise physical properties or complex mathematical parameters by the user should be avoided. For speed and simplicity, the number of inputs and operations should be minimised and it should be clear to the user what these are. Similarly the results should be presented in a clear and concise manner displaying only the most relevant information using familiar expressions and units where appropriate.

In General

In general terms, a Graphical User Interface (GUI) should be clear, concise and easy to read. The following keywords sum up the main aims of all good graphical design.

- Simplicity
- Consistency
- Familiarity

When dealing with human/computer interaction the dynamic interface between the graphical representation, the operation of the software and the user, also have to be considered. The operation and communication between the user and the software should also be simple, rapid and easy to use. In these terms, the following keywords sum up the aims of good interface design.

- Immediate
- Continuous
- Reversible
For example, the use of “Undo” facilities enables better interaction by allowing mistakes to be made without major hindrance to the user. This may make the user more comfortable when experimenting with unfamiliar software [1].

When creating the user interface for the design advice system an iterative, two stage design process was used. See Figure 6.1.1. The first stage concentrated on establishing the best way to enter data and control the input of information as well as identifying the optimum method of displaying the results. This was mostly conducted on paper, using flow charts and sketching. The second stage involved coding the interface and iteratively testing and improving it according to the overall aims [1].

![Figure 6.1.1. GUI design and development process.](image)

To meet these requirements a graphical user interface was constructed to establish the best methods for defining the inputs to the system. These were initially sketched on paper, as in the examples shown in Figures 6.1.2 and 6.1.3. This involved choosing the simplest way for the user to define the parameters required by the system. Some of these could be simple fields into which the user could type figures. For
example, in the first few iterations of the system the object sizes were manually typed in by the user. Other parameters were better viewed as a list of choices from which the user could select one choice. The intended production material, for example, is selected this way. Similarly the results should be presented in a clear, concise and unambiguous manner.

Figure 6.1.2. Initial sketch development of the user interface.

Figure 6.1.3. Further sketch development of the user interface.
The use of multimedia authoring software, in this case SuperCard, allowed a functional Graphical User Interface (GUI) to be constructed rapidly and simply with minimal coding. This type of software combines graphics tools with an object oriented programming language to control object behaviour, such as fields, menus and buttons. This approach saved a great deal of development time compared to the use of a programming language, such as Visual C++. This allowed many more design variations to be made. Similar authoring software has been used to develop front end user interfaces which allow small companies to access powerful simulation software [2].
6.1.1 The Initial User Interface

After some ideas for the user interface were sketched on paper, the multimedia authoring software was used to create a basic system with a simple user interface. See Figure 6.1.1.1. At this stage it was envisaged that the system would be able to run solutions with metal and plastic components and a “toggle” type selection button was incorporated to select the between them. However, due to time constraints the metal material processes were not included and this button was removed from the system. The other inputs were those identified as being of key importance when selecting rapid prototyping processes. The reasoning behind the isolation of these characteristics is given in Chapter 3.3: Selection Criteria. Most of the inputs merely required the user to type a numerical value with the exception of the material type which is selected from a pick list.

![User Inputs](image)

Figure 6.1.1.1. Initial graphical user interface for user inputs.

The second screen, shown in Figure 6.1.1.2, allowed the user to specify the intended use of the prototype parts. As with material specification, this consists of a list of test and requirement types from which the user can make a selection.
This simple interface obtained enough information from the user to allow the creation of a basic design advice system which could select an appropriate rapid prototyping solution. The results screen, shown in Figure 6.1.1.3, was similarly simple and was intended to display the selected route clearly and concisely. From the outset the results screen was split into sections relating to rapid prototyping, finishing and secondary tooling.
6.1.2 First Modifications

The user interface was almost immediately modified to be visually clearer and simpler to use. In general the interface was improved with the adoption of clearer fonts and text sizes. The fields were also rearranged into a neater format. An explanation of the required inputs was also added to the system. This information was displayed in another window and accessed by the user clicking a “help” button. Another pick list was added to allow the user to specify special features relating to the component which may affect the solution. For example, the user could indicate that the component is intended to be “transparent”. See Figure 6.1.2.1.

![User Inputs](image)

Figure 6.1.2.1. First modification of the User Input Screen.

The second user input screen, where the prototype use is specified, was also simplified. See Figure 6.1.2.2. This involved replacing the list of possible uses with four categories of prototype use based upon the physical demands expected of the prototype. The reasoning behind these categories is explained in Chapter 3.4: Prototype Classification. As with the first screen an explanation of these categories could be accessed by the user by clicking a “help” button.
The results screen, shown in Figure 6.1.2.3, was improved by the addition of explanation material which can be accessed by the user through a “More Info” button. At this stage in the development this button opened a window containing a short piece of text that described the secondary tooling process shown in the results.
6.1.3 Integrating the automatic derivation of object data

The user interface had to be greatly altered when the automatic derivation of object data was introduced to the system. This necessitated the addition of controls to select and process the desired STL file and read in the results of the STL interrogation process. Some of the properties derived from the STL file are then displayed in fields on the input screen. This provides the user with an opportunity to observe properties which they may not be familiar with, such as number of facets, and also check that other properties are as expected. The user then has only a few remaining inputs to type into the relevant fields before progressing to the second screen. See Figure 6.1.3.1.

![Modified User Input screen using automatically derived object data](image)

Although the interrogation of the STL files is carried out by a separate piece of software it is automatically called by the multimedia software and as such its operation is invisible to the user. This was made possible by using cross application communication software, described in greater detail in Chapter 6.4: Cross Application Communication.

The derivation of the object data is described in Chapter 6.5: Derivation of Information from the STL File Format. When the interrogation is complete the user is presented with a shaded three dimensional image of the STL file in a separate window adjacent to the input screen. This screen allows the user to alter the view and visually
inspect the object. The appearance of the image signals that the interrogation is complete and the user can read in the properties by clicking the “Read Results?” button.

The first user input screen is split into three sections. The first section is devoted to the selection and interrogation of the STL object. The second section contains fields for the object data and the third section contains the remaining user input fields in which the user can type in values. Each section has a help button associated with it. In addition a “Getting Started” help button was also included to introduce new users to the system. A “Quit” button was added on this screen which would quit the system and automatically close down the interrogation software.

At this point, to make the process easier for the new user, a colour coding was applied to the system. Buttons and fields relating to the users required inputs and actions were given green borders, whilst the help and explanation buttons were given red borders.

**Development Information**

To aid the development of the design advice system at this stage two more windows were added. These were intended to be for the developer to use and were opened by buttons that are hidden from the user. Colour coding was extended to include these windows, yellow being chosen to identify windows devoted to development use only. The first window contained version information and history. See Figure 6.1.3.2. This allowed the author to record modifications and maintain the version history and correctly identify any alterations and the dates when they were implemented. The second window contained all of the data available from the STL file interrogation. See Figure 6.1.3.3. This enabled the developer to check that variables were handled correctly and no corruption of data was occurring between the interrogation software, the output text file or the multimedia authoring software.
The increased amount of information on the first user input screen meant that the other inputs had to be moved to the second screen, shown in Figure 6.1.3.4.
The second user input screen now held three pick lists for the specification of prototype use, material and special features. A revised help screen explaining these items was created for the user to access via a “Help” button. When the user leaves this screen, by clicking the right hand corner arrow, the system runs a solution. The results appear on the next screen.

The results screen was also enhanced in line with the rest of the user interface. Explanation material was made available to the user for both the rapid prototyping and the secondary tooling stages. In addition, descriptive text, diagrams and photographs were added to the explanation material. Totals for lead time and costs and a “Quit” button were also added to the results screen. See Figure 6.1.3.5.

![Figure 6.1.3.5. The results screen.](image)

### 6.1.4 The Final User Interface

The final version of the system has essentially the same user interface with a few alterations, relating mainly to the non-automated user inputs which were reduced to the essential characteristics only. Which were; the number of prototypes required, the minimum wall thickness and the accuracy desired. Another characteristic was also added at this time; maximum aspect ratio. Although this characteristic will not significantly affect the selection of rapid prototyping and tooling processes it will have an effect on the way some of these processes are applied. This version is the one used...
for the user trials described in Chapter 7.3: User Trials. A worked example of this system can be found in Chapter 7.1: Worked Example. The final versions of the user input and system output screens are shown in Figures 6.1.4.1 and 6.1.4.2.

Figure 6.1.4.1. Final version of the User Input screen.

Figure 6.1.4.2. The final output screen.
6.2 Development of the Decision Rules

The decisions the system has to make are separated into steps according to how many parts are required. If only a few parts are required the system only needs to be concerned with the selection of rapid prototyping processes. However, in economic terms, if more than a few parts are required additional secondary tooling methods must be used. These will rely (in most cases) on the use of a single master pattern produced by rapid prototyping. Thus there are two main decisions to be made. Firstly the selection of the most suitable rapid prototyping process and secondly, if necessary, the selection of a secondary tooling process capable of the producing the required number of parts.

The decision rules which select the rapid prototyping processes work according to a set of criteria specific to rapid prototyping process capabilities. Rather than attempting to compare all of the attributes of each process with a set of requirements, or each other, it was decided to prioritise the key features of an object that would have the most profound effect on the success of an RP build. Using selection by limits according to a few key characteristics would enable the system to operate much faster and eliminate redundant calculations or comparisons.

The first step was to isolate the most important object features and establish how they are expressed. The various RP processes could then be arranged according to their ability to reproduce those features. It is favourable to use features which are directly identifiable and measurable by the user. The process by which these characteristics were identified is described in Chapter 3.3: Selection Criteria.

In simple terms, processes are eliminated from the selection procedure according to their capability in a certain respect. This is done by comparing the required value with minima or maxima attributed to the RP processes. They can then be arranged into a rank list according to their capability with respect to this characteristic. If initially selected, the process would be checked against other criteria. If it should fail
any of these other criteria the system would move on to the next process in the list.

The key object characteristics identified as having the greatest effect on the selection of rapid prototyping processes were the minimum wall thickness and the accuracy required. These factors showed the greatest spread of capabilities across the various RP processes.

6.2.1 RP Process Accuracy

The accuracy obtainable with various RP processes was established in the first instance by comparing quoted figures from the manufacturers of the RP machines that are included in the design advice system. However these figures were adjusted according to direct and practical experience of the RP processes. These modifications were obtained from informal interviews with machine operators and experts in the field of RP.

Each of the RP processes were then attributed with an accuracy capability. See Figure 6.2.1.1. These will help determine the selection of a rapid prototyping process but only in combination with other key characteristics. The important factor is that these figures will eliminate unsuitable processes to narrow down the possibilities which can then be further filtered according to other key characteristics. In most cases layer thickness can be considered as broadly similar to the accuracy which is usually quoted for dimensions in the build plane. This makes consideration of layer thickness relatively redundant in selecting RP processes.
RP Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanders</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Stereolithography (Epoxy)</td>
<td>&gt;0.1, &lt;0.13</td>
</tr>
<tr>
<td>Selective Laser Sintering (TrueForm)</td>
<td></td>
</tr>
<tr>
<td>Stereolithography (any material)</td>
<td>&gt;0.13, &lt;0.5</td>
</tr>
<tr>
<td>Selective Laser Sintering (any material)</td>
<td></td>
</tr>
<tr>
<td>Fused Deposition Modelling</td>
<td></td>
</tr>
<tr>
<td>Laminated Object Manufacturing</td>
<td>&gt;0.2</td>
</tr>
</tbody>
</table>

Concept Modellers

<table>
<thead>
<tr>
<th>Modeller</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genisys</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td>Actua 2100</td>
<td>&gt;0.5</td>
</tr>
</tbody>
</table>

Figure 6.2.1.1. RP Process accuracy.

6.2.2 RP Process Minimum Wall Thickness Capability

The minimum wall thickness that the rapid prototyping machine is expected to be able to reproduce has a major influence on process selection. As with accuracy figures, the capabilities of the rapid prototyping processes are, in the first instance, taken from manufacturers literature. However these figures were modified according to direct and practical experience of using RP processes. As before, these modifications were obtained from informal interviews with machine operators and RP experts. Therefore, in this design advice system, practical limits are used. To illustrate this with an example, Laminated Object Manufacturing is capable of producing wall thicknesses of as little as one millimetre. However, walls this thin are too delicate to broken out from the waste material without damage. Therefore the actual practical limit is much greater than the quoted process capability.

Each of the RP processes were then attributed with a minimum reproducible wall thickness. See Figure 6.2.2.1. These figures, in combination with other key
characteristics, such as accuracy, will help determine the selection of a rapid prototyping process. The important factor is that these figures will eliminate unsuitable processes to narrow down the possibilities which can then be further filtered according to other key characteristics.

<table>
<thead>
<tr>
<th>RP Processes</th>
<th>Minimum Wall Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanders</td>
<td>&lt;0.3 mm</td>
</tr>
<tr>
<td>Stereolithography (Epoxy)</td>
<td></td>
</tr>
<tr>
<td>Selective Laser Sintering (TrueForm)</td>
<td>&lt;0.6 mm</td>
</tr>
<tr>
<td>Stereolithography (any material)</td>
<td></td>
</tr>
<tr>
<td>Selective Laser Sintering (any material)</td>
<td>&lt;2.0 mm</td>
</tr>
<tr>
<td>Fused Deposition Modelling</td>
<td>&gt;6.0 mm</td>
</tr>
<tr>
<td>Laminated Object Manufacturing</td>
<td></td>
</tr>
</tbody>
</table>

| Concept Modellers                          |                        |
| Genisys                                    | >5.0 mm                |
| Actua 2100                                 |                        |

Figure 6.2.2.1. RP Process minimum wall thickness capability.

6.2.3 Arrangement of RP Capability

The various rapid prototyping processes were arranged according to the key characteristics of minimum wall thickness and accuracy. Most of the processes could be arranged in a rank list according to accuracy and minimum wall thickness. An exception to this rank list being Laminated Object Manufacture. Unlike most RP processes, which scan the perimeter and cross sectional area of the build layers, LOM only scans the perimeter of the layers. This difference coupled with the inexpensive nature of the build material means LOM is much better suited to parts with large sections and thick walls. Therefore the first step in the selection process is to identify parts with very thick walls or sections and, assuming LOM can produce the parts to the required accuracy, select the LOM process for the production of those parts.
The remaining RP processes can be ranked according to their capability with respect to accuracy and wall thickness. In most cases RP processes which can reliably produce smaller wall thicknesses are correspondingly more accurate. Therefore the optimum RP process will be selected according to accuracy and then checked against the wall thickness required. Assuming both characteristics are satisfied, the process will be selected. If not, the selection move on to the next process in the rank list. If the required parameters are not possible with any of the RP processes stored in the system, the user will be notified at the input stage. This prevents unnecessary computer processing which will ultimately not produce a usable result.

**Coding**

The rank list of rapid prototyping processes, according to the key characteristics of accuracy and minimum wall thickness, can be coded as a switch case control structure.

In the actual system other rules are included with each process in the rank list to account for other parameters which may affect the suitability of the RP process for a given part. To illustrate this with an example; The Sanders process possesses very high accuracy and is capable of reproducing very thin walls. However it has a limited build envelope of just 150mm cubed and it is an extremely slow process. To account for this, under the Sanders case statement in the rank list, there are lines of code which asses the size of the object to see if it economically reasonable to build the part using this process. Note that this is not a question of *capability*, which is judged according to the key characteristics, but a matter of *practical or economic feasibility*. Each process case statement also has lines of code which call subroutines which calculate the associated build times and costs.
6.2.4 Secondary Tooling Selection

Selection of secondary tooling processes is performed initially according to the service life of the tool. This is the number of mouldings that can be expected before the tool degrades below acceptable levels. Tooling methods can be simply arranged into a rank list according to predicted tool life. A process will be selected from this list to satisfy the user input “number of prototypes required”. Once selected it will be assessed according to other features. For example, many secondary tooling processes have an inherent size limit. This limit will be checked against the object data and if the process is found to be unsuitable, the system will move to the next process in the rank list.

6.2.5 Aspect Ratio Considerations

One of the user inputs required relates to the maximum aspect ratio of any feature of the part. This characteristic may not have a great effect upon the selection of rapid prototyping processes but needs to be considered when assessing the suitability of some secondary tooling applications. For many of these processes deep narrow slots or holes may prove difficult to form. Similarly tall thin features may prove problematic due to the weaker nature of many of the tooling materials in comparison to steel.

To account for these problems the user is asked to estimate the maximum aspect ratio of features on the object. If this proves to be beyond the capabilities of the secondary tooling process that has been selected by the system, an additional piece of information is supplied on the results screen. This will indicate to the user that machined inserts may be required for these features and the cost and lead times will be increased accordingly.
6.3 Development of Quotation Rules

6.3.1 Background

When developing guidelines for the estimation of the costs involved in producing parts by rapid prototyping (RP) techniques several aspects need to be considered. These include commonly considered issues like: depreciation, material costs, service costs, consumables and labour. In addition there may be more specialist requirements for materials handling, servicing, utilities and safety. Even though these considerations may be of no direct relation to the target user of this design advice system, it is important to arrive at realistic estimations of cost. Therefore it is important that the methods used to calculate these estimates mirror those used by service actual providers.

Laser Service Life

Most rapid prototyping processes work in essentially the same layered fashion. Estimation of the costs associated with building on a rapid prototyping machine is usually based on how long the machine operates for. In many cases this due to the fact that the drawing process utilises a laser. The lasers are expensive and only have a limited service life. Therefore a cost per hour of laser time is necessary to amortise the cost of replacing the laser. The building process can be broken down into the deposition of a layer of build material followed by a drawing process which creates a solid cross section. The laser is consuming its service life whilst it is powered up and not just whilst scanning. Therefore the whole build time affects the laser costs. The build time will depend on how long it takes to deposit a layer of build material followed by the length of time required to draw the cross section. The draw time will be a variable depending upon the geometry of the layer being scanned. In many cases the material deposition time is fixed for each layer. With experience the operator will be able to estimate the time required to build a given object based on its size and shape.
Depreciation

Rapid prototyping machines are very expensive, ranging from £100,000 to £500,000 and as with other capital expenditure if the significant investment is to be recouped the depreciation of the machine must be taken into consideration. Where companies purchase their own machines the investment may be recouped in cost and time savings on product development. Service providers will, however, need to recover the investment within a few years and these costs will be passed to the customer.

Servicing

Due to the specialist nature of rapid prototyping machinery and, in many cases, the proprietary technology involved the servicing of the machines has to be carried out by the manufacturers or their agents. Unauthorised servicing may invalidate any warranty on the machine. This servicing is highly specialised and non-competitive and, as such, is expensive. Servicing, therefore, is normally by fixed annual contract, often costing many thousands of pounds. These costs will have to be spread over the projected use of the machine during the term of the service contract.

Materials

There are significant costs associated with the materials used in RP processes. The materials are often proprietary and therefore expensive. The material costs, even for small models, may be significant. It is generally a simple matter to account for the material used to produce a model as the volume of the object is available from either the original CAD data or the STL file being used for the build. This can be used with the cost of the material by volume to account for the material used. In the case of Laminated Object Manufacture the paper material is sold by length and the amount used will be related to the object’s bounding box size and the number of layers required to build the object. For all RP processes there is a certain amount of unavoidable material wastage and this will also have to be considered.
Consumables

All of the sundry costs involved also have to taken into consideration. These will depend upon the nature of the machine but may include: power, water cooling, air conditioning, extraction, protective clothing, handling and cleaning materials. There may also be more specialist consumables required. For example, for safety reasons Selective Laser Sintering machines require a nitrogen supply to purge the build environment. Another example would be the ultra violet fluorescent tubes used in the post curing apparatus required for stereolithography which have a limited service life.

Labour

Although rapid prototyping machines are increasingly easy to operate there is still a certain amount of labour involved in setting up the build and removing the models from the machine. This may involve arranging, checking and creating the necessary computer files for the build, adding build material when required, and removing and cleaning of the finished part from the machine. Depending upon the type of machine this may vary from a few minutes to an hour or so. However, once a procedure is established for a given machine the time taken will be relatively independent of the object and therefore the set up cost involved for each build may be fixed. Cleaning and servicing of the machine may also need to be taken into consideration.

Finishing

All parts produced by rapid prototyping techniques require a certain amount of cleaning and finishing once a build is complete. These tasks are almost entirely manual and the costs involved therefore are based on labour. There may be other costs incurred for finishing materials and consumables. Finishing may be considered in two stages; Firstly the completed part must be removed from the machine and cleaned of waste build or support material. Some parts may require post curing or sealing. This may be considered necessary and the costs incurred added to the build cost.
Secondly the part may be finished to provide a certain appearance or surface texture. The texture required will depend on the purpose the prototype is built for. This finishing may be optional and the costs involved may be considered as a separate task.

Summary

To simplify matters the guidelines for estimating the cost of a build can be collected into a cost per hour of build time plus some fixed costs for each build. Many of the costs associated with running a machine are directly proportional to the build time. Other costs can then be absorbed into a single cost per unit time. This allows machine operators to quickly arrive at an estimated cost based on details of the object to be built.

The following examples of estimation routines are based on those developed both for this study and subsequent commercial application, at the DERC Rapid Prototyping Unit, Cardiff, UK [3].
6.3.2 Stereolithography Build Cost Estimation

This method is based on a spreadsheet initially developed in conjunction with this study and the commercial service at the DERC in 1995. The spreadsheet allowed the DERC to quote for stereolithography jobs based on the characteristics of the machine and a good sketch of the object showing the size in each axis. An estimate of the volume would also be useful. To simplify the matter the object would be split into five regions for which a cross sectional area would be estimated.

The calculations are based on the SLA 250/40 machine installed at the DERC. The key characteristic affected by the machine specific quotation is the laser scanning time. This would have to be altered slightly for different types of stereolithography machine. For simplicity, in this study, only one quotation rule is used. The spreadsheet, shown in Figure 6.3.2.1, was expanded to include information derived from the STL file [3].

![Figure 6.3.2.1. Stereolithography quotation spreadsheet.](image)

It is also worth noting here that this method can be modified to create quotation rules for other rapid prototyping processes which operate in a similar manner. For example the way in which Selective Laser Sintering operates is in essence the same as
stereolithography. The process steps requiring laser scanning of borders and fills followed by a recoating time. Although it would be a simplification, this basic quotation rule can be used to estimate costs for various RP processes once certain characteristics of layer scanning and material deposition have been ascertained for each process.

**Theory**

The object is split into five regions in the z axis. A draw time is estimated for each region based on the scanning speed of the laser and the cross sectional area of the slice. This is multiplied by the number of layers in the region. This is found by dividing the height of the region by the layer thickness. The draw time for each layer is then multiplied by the number of layers in the region and divided by 60 to get the result in minutes. There is also an associated fixed time required to recoat each layer. The total fixed time is the recoat time multiplied by the total number of layers. The build time is also estimated for the support structure.

The material cost is found by multiplying the volume of resin used by a conversion factor to obtain the mass of resin used and multiplying that by the cost per kilogramme. The draw time for each region is added to the fixed time and the support allowance to get a total time. This is multiplied by the hourly rate to give a build cost. The material cost is added to this to arrive at a total cost. Finishing cost is subsequently added. In this case, for the ACES build style the scan time measured on an SLA 250 is set to 0.04 seconds per mm with a layer thickness of 0.15 mm.

This method becomes less reliable at extremes of part size. Very small parts result in costs which are too low to take into account the minimum costs required to cover data preparation and machine set up. This is corrected by the addition of a set minimum charge. Conversely, very large parts result in costs which are proportionately too high. This is not a significant problem as parts in this size range are usually beyond the build size limit of SLA machines. Large parts are often split into
smaller sections, built separately and assembled later.

**Method**

Inputs: Model Dimensions STL Data

Constants:
- Layer thickness = 0.15 mm
- Resin cost per kg = £500

Formulae:
- Number of layers = \((\text{total height in } z \text{ axis} / \text{layer thickness})\)

Region height 1 in mm = \((1\%\text{of total height in } z) - (\text{minimum } z)\)
Region height 2 in mm = \((25\%\text{of total height in } z) - (1\%\text{of total height in } z)\)
Region height 3 in mm = \((50\%\text{of total height in } z) - (25\%\text{of total height in } z)\)
Region height 4 in mm = \((75\%\text{of total height in } z) - (50\%\text{of total height in } z)\)
Region height 5 in mm = \((99\%\text{of total height in } z) - (75\%\text{of total height in } z)\)

Number of layers in region = \((\text{region height} / \text{layer thickness})\)

Total fixed time = number of layers * recoat time

Draw time for slice in minutes = (cross sectional area * scan time) / 60

Draw time for region = draw time for slice * number of layers in region

Total draw time in hours = sum of region draw times / 60

Material Cost = \((\text{volume} * \text{conversion factor}) * \text{Cost per kg}\)

Build Cost = ((Total Build Time + Fixed Time + Support allowance) * 70)

Total Cost = Build Cost + Material Cost
6.3.3 Laminated Object Manufacture Build Cost Estimation

This method is also based on a spreadsheet developed at the DERC in 1995 for this study and subsequent commercial application. The spreadsheet allowed the DERC to quote for laminated object manufacturing jobs based on a good sketch of the object. As with the stereolithography spreadsheet the object is split into five regions for which the complexity can be estimated. In these complexity can be thought of as the amount of laser scanning required. In mathematical terms this would be calculated as the perimeter of a given slice through an object.

The calculations are based on the LOM 1015 machine installed at the DERC. The key characteristics affected by the machine specific quotation are the laser scanning time, heater movement time and paper feeding speed. These would have to be altered slightly for different types of LOM machine. For simplicity, in this research, only one quotation rule is used. The spreadsheet, shown in Figure 6.3.3.1, was expanded to include information derived from the STL file [3].

```
x extent 40.0000 mm
y extent 33.0000 mm
z extent 28.0000 mm

Layer thickness 0.2032 mm
Start up 1.0000 hours
Cost per metre 0.55 pounds
Draw speed 90.0000 mm/s
MIN 0.0000 mm
CUT1 0.2500 mm
CUT2 6.2500 mm
CUT3 12.5000 mm
CUT4 18.7500 mm
CUT5 24.7500 mm

JIFERI 206.0000 mm
JIFERI 206.0000 mm
JIFERI 206.0000 mm
JIFERI 206.0000 mm
JIFERI 206.0000 mm

Total number of layers 133.0315
Region height 1 0.2500
Region height 2 6.0000
Region height 3 6.2500
Region height 4 6.2500
Region height 5 6.0000
Number of layers in region 1 2303
Number of layers in region 2 295276
Number of layers in region 3 307579
Number of layers in region 4 307579
Number of layers in region 5 295276

Draw time for slice 1 0.0922 minutes
Draw time for slice 2 0.0922 minutes
Draw time for slice 3 0.0922 minutes
Draw time for slice 4 0.0922 minutes
Draw time for slice 5 0.0922 minutes

Draw time for region 1 0.1135 minutes
Draw time for region 2 2.7231 minutes
Draw time for region 3 2.8566 minutes
Draw time for region 4 2.8566 minutes
Draw time for region 5 2.7231 minutes

Total draw time 0.1872 hours

Filename is comp.rll

Machine Parameters
Object Parameters
Calculations

Build cost 59.36 pounds
Material cost 6.59 pounds
Total Cost 65.95 pounds

Figure 6.3.3.1. Laminated Object Manufacturing quotation spreadsheet.
**Theory**

The object is split into five regions in the z axis. A draw time is estimated for each region based on the cutting speed of the laser and the bounding box size and perimeter of the slice. This is multiplied by the number of layers in the region. This is found by dividing the height of the region by the layer thickness. The draw time for each layer is then multiplied by the number of layers in the region and divided by 60 to get the result in minutes.

The material cost is found by calculating the amount of paper used. This is the maximum length in the X axis plus a margin allowance multiplied by the number of layers. Start up time accounts for all of the operations required before building starts. This will generally take about one hour. The time for each region is added to the start up time to get a total time. This is multiplied by the hourly rate to give a build cost. To this the material cost is added to arrive at a total cost. Finishing cost is subsequently added.

For “8 Thou” paper the draw speed set on a LOM 1015 is set to 140 mm/s. However allowing for the slower drawing of curves and arcs an average speed of 90 mm/s is used.

**Inputs:**
- Model Dimensions STL Data

**Constants:**
- Layer thickness = 0.2032 mm
- Start up = 1 hour
- Paper cost per meter = £0.55

**Formulae:**
- Number of layers = \((\text{total height in z axis} / \text{layer thickness}) + 10\)
- Region height 1 in mm = \((1\% \text{of total height in z}) - (\text{minimum z})\)
- Region height 2 in mm = \((25\% \text{of total height in z}) - (1\% \text{of total height in z})\)
- Region height 3 in mm = \((50\% \text{of total height in z}) - (25\% \text{of total height in z})\)
- Region height 4 in mm = \((75\% \text{of total height in z}) - (50\% \text{of total height in z})\)
Region height 5 in mm = (99% of total height in z) - (75% of total height in z)
Number of layers in region = (region height / layer thickness)
Draw time for slice = (((4 * (extent in x axis + extent in y axis)) + perimeter) / draw speed) / 60
Draw time for region = draw time for slice * number of layers in region
Total draw time in hours = sum of region draw times / 60
Material Cost = (((extent in x axis + 50) * (Total number of layers)) / 1000) * Cost per metre
Build Cost = ((Total Build Time + Start up) * 45)
Total Cost = Build Cost + Material Cost

6.3.4 Vacuum Casting Estimation

This spreadsheet developed at the DERC and applied to this study and quotations. The spreadsheet allowed the DERC to quote for vacuum casting jobs given the size and volume of the object. The spreadsheet is shown in Figure 6.3.4.1.[3]

<table>
<thead>
<tr>
<th>Part Size</th>
<th>Tool Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 70.0 mm</td>
<td>13.0 cm</td>
</tr>
<tr>
<td>Y 60.0 mm</td>
<td>12.0 cm</td>
</tr>
<tr>
<td>Z 20.0 mm</td>
<td>8.0 cm</td>
</tr>
</tbody>
</table>

Cost of silicone £26.00 per kg
Labour rate £35.00 per hour

Volume 1248 cm cubed
Plus waste 1.1
Total volume of silicone 1372.8 cm cubed
Mass of silicone 1372.8 kg

Tool cost £35.69

Hours of labour 4 hrs
Labour cost £140.00
Plus sundries £15.00

Total Tooling Cost £190.69

Shot cost £19.07
Number of shots 20

Total Shot Cost £381.39
Total Cost £572.08

Figure 6.3.4.1. Vacuum Casting quotation spreadsheet.
Theory

There are two considerations when estimating the cost of vacuum casting, firstly there is the cost of the silicone tool and secondly, the cost of each casting taken from it. The costs are relatively simple to calculate as they depend greatly on the volume of materials used plus some labour.

Method

a) Tool Cost

The tool size should be the bounding box dimensions of the model plus 60 mm in each direction. This volume is then multiplied by 1.1 to allow for waste. This gives the volume of silicone (ignoring the model). Assuming the density of silicone is 1000 kg per cubic metre then the volume in cubic cm is approximately equivalent to the mass in grams. At the time of writing, silicone rubber is bought at £18.95 per kg and sold at £26.00 per kg. To this 4 hours labour is added at £35.00 per hour. A further £15 is added to cover sundries. The total is multiplied by a percentage markup depending on the customer discount.

b) Shot Cost

Shot cost will be approximately 10% of the tool cost. Assuming the density of resin is 1000 kg per cubic metre then the volume of each shot in cubic cm is equivalent to mass in grams. Add 80g to this to allow for waste. Resin costs approximately £40.00 per kg.

6.3.5 Epoxy Resin Tooling Estimation

Theory

Also developed at the DERC, these tooling rules are in essence similar to those developed for vacuum casting. When estimating the cost of epoxy resin tooling the costs are relatively simple to calculate as they depend predominantly on the volume of materials used plus labour costs.
**Method**

a) Tool Cost

The tool size is the bounding box dimensions of the model plus 80 mm in each direction. Calculate the volume of the bounding box in cubic cm and multiply by 1.1 to allow for waste. This gives the volume of epoxy resin (ignoring the model). Assuming the density of epoxy is 1000 kg per cubic metre then the volume in cubic cm is approximately equivalent to the mass in grams. In this case it is assumed that aluminium filled epoxy resin is approximately three time more expensive than silicone rubber, around at £78.00 per kg. As with vacuum casting, 4 hours labour is added at £35.00 per hour and a further £15 is also added to cover sundries. The total is multiplied by a percentage markup depending on the customer discount.

b) Shot Cost

If the tool is used to cast polyurethane resin parts the shot cost will be the same as for vacuum casting. In this case the shot cost would be approximately 4% of the epoxy tool cost. Assuming the density of resin is 1000 kg per cubic metre then the volume of each shot in cubic cm is equivalent to the mass in grams. 80g is added to this to allow for waste. Resin costs approximately £40.00 per kg. If the tool is used for injection moulding the shot costs may be lower depending on the material being used and the terms of the moulding machine operator.

6.3.6 Multiple Cavity Decision Rules

**Theory**

When estimating the cost of moulds and tooling, the overall size of the component can have an major effect. Each of the secondary tooling processes used in this system have a life span based on the number of mouldings they can produce before the tool degrades below acceptable levels. They also have limits, some absolute some practical, on the size of tool that can be reliably produced.
However, if the mouldings to be produced are small, more than one cavity can be used per tool. Given a specific secondary tooling process a rule can be established that will nest multiple cavities in a tool depending on the size of the object to be moulded. To prove the theory this rule was only applied to the vacuum casting rules. This was due to the problems associated with the SuperCard script length. However, the same theory could have been applied to any or all of the tooling processes used in the system.

Method

Where expected yields from a tooling process are low, multiple cavity tools may liberate a useful number of parts. Therefore the method explained here deals with vacuum casting using silicone rubber tools. In practice around twenty shots can be expected from a silicone tool before it degrades. For the capacity of a given vacuum casting machine a rule can be used that will designate multiple cavities when parts fall below a certain size limit. This size limit is based on the size of the object(s) plus the necessary extent of tooling material surrounding it being compared to the capacity of the vacuum casting machine in question.
6.4 Cross Application Communication

To make the system easy to use it is important that the user actions should be minimised. It was, therefore, highly desirable that the STL file interrogation carried out by the maths analysis software should be automatic and triggered from the existing user interface without requiring the user to manually invoke and use the second piece of software. The communication between the user interface software and the maths analysis application was handled using inter-application communication routines. In this case the user interface was constructed using SuperCard and the STL file interrogation was handled by Matlab. The communication between them was handled by Apple Scripts. Figure 6.4.1 shows how the different parts of the system interact in schematic form.

![Diagram showing cross application communication](image)

Figure 6.4.1. Schematic showing cross application communication.

Apple Scripts are small programs, or scripts, which can control applications and files on the Macintosh operating system. Figure 6.4.2 shows the Apple Script which
launches Matlab and passes to it the instruction necessary to trigger the interrogation of an STL file. In this example *compslice* is the name of the Matlab program which reads and interrogates the STL file and the STL filename is *screw.stl*. As can be seen the scripts are very brief and simple to understand. Apple Scripts can be written and stored as a 'run only' application. This small program will contain a set of instructions for another application to complete. Applications can trigger these Apple Script applications, the Apple Script program will be launched and the script executed. When the script is completed the Apple Script application will close itself down.

Another example is the "QUIT?" button on the user windows of the RP selection system. This launches an Apple Script that will not only quit SuperCard but also quits Matlab if it is running.

A problem was encountered when attempting to pass STL filenames from the user interface to the Apple Script. To allow Matlab to perform interrogations on many different STL files the filename had to be passed to the Apple Script as a variable. This problem was solved with the addition of an external function which allows SuperCard to compile and execute text stored in any given field as an Apple Script [4].

```
tell application "MATLAB"
    DoScript ("compslice('screw.stl');")
end tell
```

Figure 6.4.2. Apple Script to invoke Matlab.

Using these inter-application triggers ensures that all of the user interfacing can be limited to a single application so it appears to the user that they are only one piece of software. Although this example uses the Apple Macintosh operating system and software, similar inter-application communication is possible with other operating systems.
**Operating Sequence**

The two applications operate as follows: In the first ‘User Input’ card the user selects the STL file they wish to investigate. SuperCard takes the name of this STL file and puts it into an Apple Script which instructs Matlab to read the STL file and perform the various calculations on it. Matlab also produces a shaded image of the STL file. The image appears in a window adjacent to the ‘User Input’ window.

Meanwhile Matlab writes a text file containing the results of the interrogation. This file uses the STL filename with a ‘.ret’ (meaning returned) suffix appended. SuperCard can then read this ‘returned’ file and put the results into the corresponding variables in SuperCard. Some of these results will be visible to the user and they will appear to in the corresponding fields in the ‘User Input’ card (the middle section of the ‘User Input’ card). The user then fills in the remaining fields (the bottom section of the ‘User Input’ card) and proceeds to the next card.

Note that the user never has to leave the SuperCard environment. With the exception of the rendered image of the object appearing, Matlab’s operation is invisible to the user. The window containing the shaded image contains sliders and buttons to enable the user to view the object from any angle.

On the second ‘User Input’ card the user then selects items from pick lists to specify the intended use of the prototype, the production material and any special features the object may require. After selecting from the lists the user proceeds by clicking the arrow and the selection of the most appropriate route is then handled within SuperCard as previously described.

If the user wishes to retry the selection using the same STL file they do not need to process the STL file through Matlab again, instead SuperCard can simply reread the returned file which is stored. For this reason there are separate buttons in the ‘User Input’ window for ‘Processing’ the STL file and ‘Reading’ the returned file.
6.5 The information derived from the STL file format

6.5.1 Property Groups

1) File properties derived from the STL file format include:
   - Filename
   - Number of facets
   - File size in bytes

2) Geometrical Properties derived from the STL file format include:
   - Extents and overall size in X, Y, and Z axes
   - Surface area
   - Volume
   - Bounding Box Volume

3) Slice properties derived from the STL file format include:
   - Number of lines
   - Perimeter of cross section
   - Cross sectional area
   - Bound slice area

In addition other properties are calculated from formulae relating the above properties to each other or to constant values.

6.5.2 File Properties

Binary STL files begin with a header which contains information about the file. The filename is given in the header and will be appended by the suffix .stl. The number of facets is also given. When the STL file is used the number of facets read can be compared to the number quoted in the header to check that the file is complete and uncorrupted. The file size in bytes is also quoted in the header. The file size directly relates to the number of facets in the STL file plus the header.
To properly establish the format of a binary STL file a copy of the format was provided by 3D Systems Inc. A program, written in C, was provided which would read in an STL file, check the validity and calculate the volume of the object. Although this program, called DUMPSTL was written specifically for use on UNIX (Silicon Graphics) computers a text listing illustrated the workings of the program [5].

The first issue to be addressed was to write a program in Matlab that could successfully read in a binary STL file. Using the format provided in DUMPSTL the numbers could be read in in the correct order and arranged into a matrix within Matlab. Initially problems were encountered which resulted in incorrect numbers in the matrix. This problem was traced to a byte ordering problem. This was corrected by changing the read parameter to IEEE floating point with 'little-endian’ byte ordering.

In the file the triangles are listed, each triangle has 12 pieces of data. Three for the i, j and k elements of the normal vector and the x, y and z coordinates of the three vertices. This gives a 12 by n matrix, where n is the number of triangles. As the Student Edition of Matlab was used there was a limited matrix size of 16,384 elements. This limits the maximum size of STL file that can be read into Matlab to 1365 triangles. This size limit however did not hinder the development of programs which use the STL data.

The matrix format is illustrated below. The matrix containing all the facets is called ‘alldata’. Each line represents a single facet, therefore, the number of lines is equal to the number of facets.

<table>
<thead>
<tr>
<th>Normal vector</th>
<th>First Vertex</th>
<th>Second Vertex</th>
<th>Third Vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3</td>
<td>4 5 6</td>
<td>7 8 9</td>
<td>10 11 12</td>
</tr>
<tr>
<td>i j k</td>
<td>X1 Y1 Z1</td>
<td>X2 Y2 Z2</td>
<td>X3 Y3 Z3</td>
</tr>
</tbody>
</table>
Using a 'patch' command Matlab can also generate a three dimensional shaded image of the STL file as it is read in. Standard Matlab routines can then be used to manipulate the view of the object.

Once the file could be successfully read some basic operations could be performed. These included displaying the contents of the header; filename, number of facets, and file size.

### 6.5.3 Geometrical Properties

The STL file format is basically a list of $x$, $y$ and $z$ coordinates relating to triangular facets. It is, therefore, a relatively simple matter to sort through the list to extract the minima and maxima for each axis. These coordinates represent the extents of the object. If the minima are subtracted from the maxima the result will be the overall size of the object in the three axes. Multiplying these lengths in each axis will give the volume of a cuboid bounding the object.

The STL file format is made up of many triangles approximating the shape of an object. Using three dimensional geometry the area bound by each triangular facet can be found. Therefore the sum of the areas of all the triangles will be the surface area of the object. As an extension of this, the volume of the object can be calculated by creating a tetrahedron from each triangular facet and calculating its volume. To do this a fourth, fixed point has to be used. To simplify the maths the origin is used as the fixed point. The vertices of the triangular facets are numbered according to the right hand rule and will therefore determine which is the material side of the facet. i.e. inside surface [6]. The facet normal points away from the material surface. See Figure 6.5.3.1. If this order is taken into consideration a sign will be associated with the volume of the tetrahedron, therefore when the volumes of all the tetrahedra are summed, the result is the bound volume of the object.
Listed with each set of coordinate data relating to a facet is a vector of the facet normal which points away from the material, i.e. the outside surface. The normal vector could also be used to distinguish between positive and negative volumes but would add unnecessary code and processing time.

**Size and Extents**

To explain the working of the program sections which provide the properties the following examples are given.

To obtain the extents from the STL file Matlab commands for retrieving the minima and maxima from a matrix were used. This was done for the coordinates in each of the axes. Subtracting the minima from the maxima obtained the overall object size in the three axes. The midpoint of these sizes in addition to the minima located the centre of extents.

The volume of the cuboid bounding the object was also found by simply multiplying the lengths in each axis.
Surface Area

The next property to be ascertained is the surface area of the object. This is done by calculating the area of each triangular facet. The area of a triangle in three-dimensional space can be calculated from the vector product of the relative positions of the vertices. For the general triangle with vertices KLM this appears as follows [7].

\[
0.5 \sqrt{ \left( (y_L - y_K)(z_M - z_K) - (z_L - z_K)(y_M - y_K) \right)^2 + \\
\left( (z_L - z_K)(x_M - x_K) - (x_L - x_K)(z_M - z_K) \right)^2 + \\
\left( (x_L - x_K)(y_M - y_K) - (y_L - y_K)(x_M - x_K) \right)^2 }\]

Volume

The volume of an STL file can be calculated by treating each facet as one face of a tetrahedron. A volume is calculated for each facet by using a fixed fourth point, in this case the origin is used to simplify the maths. The direction the facet is facing is given by the order of vertices obeying the right hand rule (positive being clockwise if the plane is viewed in the same direction as the normal). When the direction of the facet is taken into consideration the resulting volume may be positive or negative. In simple terms the volume associated with a facet which faces away from the origin will be positive and one facing towards the origin will be negative. See Figure 6.5.3.2. Thus summing the volumes will result in the bound volume of the object being calculated.
The volume for the general tetrahedron, vertices KLMN, is found by the determinant of three vectors obtained by subtracting one vertex from the other three and dividing by six. In this general case the subtracted point is K [7].

\[
\frac{1}{6} \begin{vmatrix}
(x_L - x_K) & (x_M - x_K) & (x_N - x_K)
\end{vmatrix}
\end{vmatrix}
\]

\[
(y_L - y_K) & (y_M - y_K) & (y_N - y_K)
\end{vmatrix}
\]

\[
(z_L - z_K) & (z_M - z_K) & (z_N - z_K)
\end{vmatrix}
\]

For simplicity the origin (zero) is used for the subtracted vertex. This simplifies the determinant to the following.

\[
\frac{1}{6} \begin{vmatrix}
(x_L) & (x_M) & (x_N)
\end{vmatrix}
\end{vmatrix}
\]

\[
(y_L) & (y_M) & (y_N)
\end{vmatrix}
\]

\[
(z_L) & (z_M) & (z_N)
\end{vmatrix}
\]

Using the evaluation of a third order determinant the result below is obtained.
Inferred Properties

Using some of the properties calculated directly from the STL data other, more subjective, properties could be inferred. These properties were found to investigate whether they could provide any useful assumptions about the size or shape of an object. These characteristics were found by comparing other properties.

Firstly the volume of the object was compared to the bounding box volume. It was hoped that this may give indication of the 'bulk' of the object. If an object had a volume close to that of its bounding box, it could be assumed to be heavy sectioned or bulky. This inferred property, 'bulk', was expressed as a percentage.

Secondly, the surface area of the object was compared to its volume. It was hoped that this may also give an indication of the average section thickness of the object. The assumption was based on a cube; i.e. the side length of a cube can be found by dividing the volume by the surface area and multiplying the result by 6. This inferred property, 'thickness', although not directly useful, may be used to infer an average section.

Function Control

The above calculations are all performed in one complete Matlab program. This main program calls another program to perform the slicing and calculate the associated properties. Slices are taken at five levels. As all objects vary in height the height at which the slices are taken is a function of the height of the object. In this case
the slices area taken at 1%, 25%, 50%, 75% and 99% of the objects height. By observing how the cross sectional area varies over the object’s height certain assumptions can be made about the shape of the object. This information is most useful when estimating rapid prototyping build times, and therefore costs. The slicing program, called ‘csarea’, returns the results into a matrix, called ‘jn’, in the main program, where n is the slice number.

More slices could provide a closer approximation. This could become a user selectable option. Taken to the extreme the slices could be taken at the same level as the RP build machine, usually between 0.1 and 0.2 mm. This would enable very accurate estimations but would involve very slow processing times and the result would be too specific considering the aims of the system.

Once all of the results are returned they are stored in a matrix. The contents of this matrix are then written into a text file using a standard delimiter between the entries, in this case the % sign is used. The file has the name of the STL file with ‘.ret’ appended. This text file can then be read by SuperCard.
6.5.4 Slice Properties

In an attempt to derive more information from the STL file format a slicing algorithm was written. A program was written in Matlab that would take a slice through an STL file at a user defined height. An additional program was written to display the slice if required. The routine required to slice an STL file is relatively straight forward and works by finding the intersection of a plane and the lines describing the edges of the facets.

The data describing the slice is made up of the normal vector (projected on to the slice plane) and the end points of lines formed by the intersection of a triangular facet and the defined slice plane. The data is stored in a 7 by n matrix, where n is the number of lines created by the slice. The matrix also contains the original number of the triangle from which the intersection line was created. For the purposes of this system the slices are made in the x-y plane, perpendicular to the z axis.

<table>
<thead>
<tr>
<th>Normal vector</th>
<th>First End Point</th>
<th>Second End Point</th>
<th>Triangle Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2</td>
<td>3 4</td>
<td>5 6</td>
<td>7</td>
</tr>
<tr>
<td>i j</td>
<td>X₁ Y₁</td>
<td>X₂ Y₂</td>
<td>T</td>
</tr>
</tbody>
</table>

**Perimeter**

Using two dimensional coordinate geometry it is therefore a simple matter to calculate the length of these lines by calculating the distance between two points. By summing the absolute lengths the perimeter can also be calculated. Using a matrix called ‘bigout’ this was coded in Matlab.

**Cross Sectional Area**

Calculating the cross sectional area is not as simple as it may initially appear, as the direction of the lines will depend on the orientation of the associated facet. To determine the inside of the cross section from the outside the normal vector has to be used. The normal vector will point away from the object. To calculate the cross
sectional area a reference axis is chosen and a trapezium is formed by taking ordinals from the end points of the section line to the reference axis. Using coordinate geometry the area of these trapezia can be found. By accounting for the angle formed between the normal vector and the reference axis, areas can be given a sign according to whether they face towards or away from this axis. Summing the areas will then give the cross sectional area.

Figure 6.5.4.1 shows a slice through a cuboid STL file. The normals are shown, as are two trapezia. The area marked A would be a negative area and the area marked B would be a positive area. The x axis is the reference axis and therefore the positive and negative trapezia can be identified as those formed with lines whose normal points towards the x axis. Only one component of the normal vector is required, in this case the j component. If this is less than zero the normal is pointing towards the reference axis. It must be noted that this formula will only work if the whole of the object is positioned in the positive octant. The area of a trapezium is simple calculate by separating it into a square and a triangle and summing those areas.
Inferred Properties

Additional properties were inferred from the slice data. Firstly the bound area for the slice was calculated by obtaining the minima and maxima in the x and y axes and multiplying them together. Secondly, to indicate an average section the square root of the cross sectional area, called ‘wall’, was calculated. Finally a ratio of the bound area to the slice area was calculated as an approximate indication of the complexity of the cross section. This property, is called ‘ratio’, in the code.

The results of all the operations conducted on the slice data were put into a matrix including: the number of lines in the slice, the perimeter, the cross sectional area, the bound area, the square root of the cross sections area and the ratio of the bound area to the cross sectional area.
6.6 References


3) P. Freeman, 1995 to 1998. Private communication. DERC RP Unit, Cardiff, UK.


7.1 Worked Example

The operation of the selection system is described in the following example. When the application is opened the user is greeted with the first window, shown in Figure 7.1.1, which is concerned with the user inputs. The user selects the STL file they wish to use by clicking the **Pick an STL File** button. This opens a default folder containing the STL files. If the STL file is stored elsewhere the user can browse for it. The user selects the STL file they wish to use from the list. In this example **clip.stl** is the file being used. Clicking the **Process STL File** button automatically triggers the mathematical analysis software to read the STL file and perform the various calculations on it. The mathematical analysis software also produces a shaded image of the STL file. The image appears in a window adjacent to the user inputs window. The user can change the viewing angle in the image window to visually inspect the STL file.

![Figure 7.1.1. First User Input Window.](image)

When the interrogation of the STL file is complete the three dimensional shaded image will appear, as shown in Figure 7.1.2. This signals to the user that the information is ready and they can proceed by clicking the **Read Results ?** button.
The resulting values will then appear in the corresponding fields in the user input card (the middle section of the user input card). The user then fills in the remaining fields (the bottom section of the user input card). These fields include: the number of prototypes required, minimum wall thicknesses, maximum aspect ratio and accuracy. The user enters values into these fields. In this example; the number of prototypes required is 250, the minimum wall thickness is 1.5 mm, the maximum aspect ratio is 1:1 and the accuracy desired is 0.2 mm.

The user can then proceed to the next card by clicking the arrow in the bottom right hand corner of the window. Note that to the user the system appears to be a single piece of software.

On the second input card, shown in Figure 7.1.3, the user selects items from pick lists to specify the intended use of the prototype, the production material and any special features the object may require. In this example the prototype use category selected is 'Not Property Specific', special requirements selected is 'None', and the material selected is 'ABS'. After selecting items from these lists the user proceeds by clicking the arrow at the bottom right hand corner of the window and the selection of the most appropriate route is then processed.
Each section of the input cards has a Help button. Clicking the help button opens another window (below the user input windows) which describes the required inputs. Figures 7.1.4, 7.1.5, 7.1.6 and 7.1.7 show the help windows for the various sections of user input. There are also safeguards which will give an error message if invalid data is entered. The error message will describe which input is invalid and suggest a more suitable value or indicate appropriate limits. Closing the error message window will clear the field with the erroneous entry and place the cursor in the field ready for the user to re-enter a value.
Once an STL file has been processed the information is stored by the system. Therefore, if the user wishes to retry the selection using the same STL file they do not need to process the STL file again. Instead the user can simply reread the data by
selecting the STL file as before and clicking the Read Results ? button. Thus saving
the processing time associated with interrogating the STL file. For this reason there are
separate buttons in the user input window for ‘processing’ the STL file and ‘reading’
the object data.

When the system has calculated the most appropriate prototyping route it is
displayed in the results card, shown in Figure 7.1.8, which appears in place of the input
cards. The results are shown as a breakdown of the recommended route describing the
processes to be used along with the costs and lead times associated with them. At the
bottom of the window are totals for cost and lead time. The user can then print the
results screen or perform another selection.

Figure 7.1.8. The Results Window.

In this example Stereolithography, Selective Laser Sintering and Fused
Deposition Modelling have been found to be equally capable of the creation of a master
pattern which will then be used in the creation of Spray Metal Tooling. This will be
used to injection mould the 250 prototypes required. The estimation for total lead time
is just under five working days with a total cost of £1673.00. In addition there is advice
concerning part finishing.
On the results page there are **More Info** buttons associated with each section. Clicking these buttons will provide a detailed explanation of the processes displayed in the corresponding section of the output. From these explanations other windows can be opened to show diagrams and photographs of the processes, machines and parts. Figure 7.1.9 shows the explanation windows. There is one window offering an description of the selected rapid prototyping processes and another describing the selected secondary tooling process.

![Rapid Prototyping Method Description](image1)

**Rapid Prototyping Method Description**

**SLA, FDM, SLS**

In this case any of the above rapid prototyping methods would prove suitable. All can produce models within an accuracy of 0.4mm and thin walls down to around 0.6mm.

SLA uses liquid resins which solidify when exposed to UV light. The layers are created by a laser scanning onto a thin film of liquid thus solidifying it. Click the button marked SLA below for more information.

FDM creates layers by depositing a fine extruded bead of thermoplastic material. Click the button marked FDM below for more information.

SLS creates layers by locally melting finely powdered thermoplastic material using a scanning laser. Click the button marked SLS below for more information.

![Tooling Method Description](image2)

**Tooling Method Description**

**Spray Metal Tooling**

This process involves creating a master pattern incorporating a split line and spraying a layer of metal alloy, usually zinc based, over it to create the tool face. The sprayed shell needs to be about 10mm thick. The rest of the tool being built up with metal filled epoxy resin or chemically bonded ceramic. Copper pipe may be incorporated into the backing material to provide cooling lines. The resin tool will replicate the surface very well so it is important that the master pattern is finished with the required surface finish. The master pattern may well be damaged when it is removed from the shell. The tool face will be slightly porous so tool life will be limited; a maximum 2000 shots should be possible using unfilled plastics, this figure will drop for increasingly filled plastics. Tool production should take 2 to 3 days. Setting up for injection moulding should take about a day and production rates will be a little slower than those achieved in steel tools, around 1800 per day.

**Tooling Method Warnings**

Spray metal tools usually fail due to chipping at the split line leading to increasingly large amounts of mould flash on parts. This damage often occurs upon part ejection. Due to these constraints parts should have generous draught angles and radii. Although parts are possible with light radii and shallow draughts angles the life of the tool will fall accordingly. Parts which require tall thin features may have to have machined inserts which can be incorporated into the tool. As a guide the aspect ratio of tall thin slots or holes should exceed 4:1 a machined insert may be required.

![Figure 7.1.9](image3)

*Figure 7.1.9. The rapid prototyping and secondary tooling explanation windows for version 13.*
Diagrams can be displayed to further explain the operation of the RP processes by using buttons at the bottom of the rapid prototyping window. Buttons on the diagram window can be used to display photos of the corresponding types of RP machine. Figure 7.1.10 shows windows containing a diagram illustrating the stereolithography process and a photograph of an SLA 350 machine.

Figure 7.1.10. The diagram and photo windows for version 13.
7.2 User Trials

Once completed the system was assessed by potential users. Three types of test were conducted to investigate the performance of different aspects of the system. The areas of interest were; the ease of use, the usefulness of the results, in format and content, and the validity of the results. To accomplish these aims trials were conducted with different types of user. A brief guide was given to trial users to introduce them to the system and the purpose of the trial. See Appendix 6: User Guide for Trials.

Initial trials investigated the system’s ease of use. The second set of trials was aimed at the target user and was intended to assess their overall reaction. The validity of the results was assessed using subjects with a sound knowledge of rapid prototyping and product development.

7.2.1 Target User Trial Reactions

In these trials the subjects were working designers with a sound knowledge of product development. Previous knowledge of rapid prototyping was not expected. They were asked to supply an STL file of an object intended to be produced by injection moulding. This STL file had to be within the guidelines supplied to each subject. The target user reactions were as follows:

Target User 1

The system is self explanatory. The user inputs required presented no problems and were to hand. Completing the inputs did not take a significant amount of time. The results appeared clear and valid, although more detail about the costings would be useful. Also, a more detailed explanation of which features most heavily influenced the decision of the most suitable rapid prototyping process would be desirable. Where the results contain a choice of equally suitable rapid prototyping processes, the explanation material should do more to help the user distinguish between the alternatives.

This company designs and manufactures joysticks for various control applications.
Target User 2

The system is self explanatory. There may be too few inputs required, and the input procedure seemed brief. The explanation material was found to be adequate. The system did not take too long to use. The results were clear, although more information may be useful if it was displayed on the results screen rather than in the help windows. Reference to materials in the results page could be clearer. Some materials should include an indication of the process used when referred to on the results page. In general the system was easy to use and there was enough information supplied. Interest in a capability for metal parts as well as plastic parts was expressed.

This company designs and manufactures hearing aids.

Target User 3

The program seemed to be well laid out and self explanatory. The results were laid out in a clear manner. The information that was required also seemed to be logical. There could be more clarification of the inputs required and their limits prior to using the system, possibly in the form of a tutorial or worked example. The controls which alter the three dimensional shaded image are not explained adequately.

This company designs and manufactures electrical light fittings and other trade mouldings.

Target User 4

The interface was reasonably self explanatory although each of the available help screens had to be used. It was commented that the visual impact of the first screen could be better, to lead the eye naturally to the “Getting Started” button. The results were presented adequately although the user was slightly skeptical about the actual figures. The user accessed the explanatory information relating to both RP and tooling and also went on to access the information relating to all of the other RP processes.

This designer is currently working on product development of electromechanical test equipment.
Target User 5

The user interface was satisfactory and not all of the available help screens had to be used. It was commented that better use of colour may help the first time user find where to start. The quit button would be easier to find if it were a different colour. The user accessed the explanatory information relating to both RP and tooling. This user also commented that this system would be well suited to use as a teaching aid for undergraduate product design students.

*This designer is currently working on all aspects of product development as a placement student at a design consultancy.*

Target User 6

The user interface was not commented on directly, although most of the help screens were not used. The view controls were used and it was commented that they were poor as they did not operate in the manner expected. However, this could be accommodated for once it became familiar. This more experienced designer had some knowledge of rapid prototyping and commented that the results seemed “about right” and would give a non-expert a good idea of the actual costs involved. It was noted that a system such as this may be extremely useful in providing estimates for internal budgeting of product development in manufacturing companies. This would allow budgets to be applied for when commencing on new projects or allocated before releasing drawings or CAD data to third parties for estimates.

It was noted that it would highly desirable to automatically identify wall thickness, draft angles and undercuts, to better account for these features in the tooling calculations.

*This designer is currently working on the product development of medical products within a small design consultancy.*
Target User 7

The user interface was noted as being "fine". The arrow buttons leading to the next page might be better shown as "Next", "Done" or "Finish" as is commonly found in Windows applications. The user went through the system very quickly only reading some of the available information.

This junior designer is currently working on product development as part of a small design consultancy and is CAD proficient.

Timings

On average users spent between 5 and 12 minutes running their first solution. Of this time, up to two minutes would be taken up by the STL file analysis. The average time taken for a new user to complete a query was approximately 8 minutes. This would usually include the use of all of the help screens and explanation material.

Subsequent uses of the system were much faster as the user no longer referred to the help screens, taking on average approximately 5 minutes. In some cases the STL processing time made up a considerable proportion of the overall query time. Processing times varied from a few seconds for simple files to just over two minutes for files with around 1300 facets. Some typical processing times are shown in Table 7.2.2.1.

<table>
<thead>
<tr>
<th>File name</th>
<th>File size</th>
<th>Number of facets</th>
<th>Processing time min : sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>new.stl</td>
<td>1K</td>
<td>12</td>
<td>0:05</td>
</tr>
<tr>
<td>comp.stl</td>
<td>2K</td>
<td>28</td>
<td>0:14</td>
</tr>
<tr>
<td>screw.stl</td>
<td>23K</td>
<td>452</td>
<td>0:47</td>
</tr>
<tr>
<td>crate.stl</td>
<td>24K</td>
<td>480</td>
<td>0:44</td>
</tr>
<tr>
<td>hin.stl</td>
<td>24K</td>
<td>480</td>
<td>1:03</td>
</tr>
<tr>
<td>anna.stl</td>
<td>41K</td>
<td>812</td>
<td>1:27</td>
</tr>
<tr>
<td>port-cov.stl</td>
<td>46K</td>
<td>918</td>
<td>1:30</td>
</tr>
<tr>
<td>oclip1.stl</td>
<td>47K</td>
<td>944</td>
<td>1:25</td>
</tr>
<tr>
<td>spool1.stl</td>
<td>66K</td>
<td>1312</td>
<td>2:25</td>
</tr>
</tbody>
</table>

Table 7.2.2.1. Table of processing time for selected STL files.
7.2.2 Expert User Trial Reactions

In these trials the subjects chosen have a sound knowledge of rapid prototyping and tooling. They were asked to comment on the decisions and estimates made assuming the object is intended to be produced by injection moulding. This STL file had to be within the guidelines supplied to each subject.

Expert User

The Expert User agreed strongly that there is a need for a computerised selection system to aid potential customers in selecting rapid prototyping and tooling routes. The criteria against which the system selects rapid prototyping processes was valid and the presentation of results was fine, although the expert user questioned the actual figures quoted for cost and lead times associated with stereolithography, suggesting that the costings were too low. The expert agreed that secondary tooling costs were, to a certain degree, fixed with additional amounts according to increasing size and complexity. There was also agreement on the basis for modifying tooling methods according to part size and aspect ratio of tall thin features.

In addition, there was a further discussion concerning the use of the STL file format and the possibilities for deriving more useful information from it. The expert suggested that the requirement for side actions on secondary tooling might be automatically identified from the STL file. Once identified a factor could be applied to the cost and lead time estimations for the secondary tooling method selected. This is discussed further in Chapter 8.2: Further Work. There followed a more general discussion about the various problems associated with rapid prototyping and tooling techniques and how the industry would progress over the next few years.

This expert user is the chairman of well established, leading European rapid prototyping and tooling bureau.
7.3 Reaction to the Trial Results

7.3.1 Problems Arising from the Trials

One of the observations of the trials was a request for more detailed information relating to the decisions made by the system. Specifically the key characteristics which gave rise to the selection of the rapid prototyping methods.

Other comments included a request for a tutorial to guide the user through an exercise. Expert user comments were made concerning the accuracy of the estimations for rapid prototyping builds.

7.3.2 Decision Tracking and Access

The inspection of decisions the system had made was achieved by adding lines of code to each of the selection rules which would output a brief explanatory piece of text to a file. After all of the decisions had been completed the text file could be accessed from the results window and read by the user if required.

Initially, adding these rules proved difficult as the controlling script was approaching the size limit allowed by the multimedia authoring package. However, a new system was created to prove the operation of the decision recording routines. This involved creating a system with limited functionality which would allow more of the script length to dedicated to the decision recording rules. Effectively this system had the higher volume secondary tooling processes removed allowing the user to perform queries requiring up to 5000 prototype parts.

Code was written which would open a text file called “tracking” and write a brief explanatory piece of text to the file. The text string is written following any previous text. Therefore this same piece of code can be used anywhere a decision is made. When a selection has been performed this text file will contain a record of all the decisions made, in the order they were made. A carriage return is written after each entry to put a line between it and any subsequent pieces of text relating to other decisions.
The multimedia authoring software can only maintain three open files at any one time. Therefore, to avoid problems associated with this, the text file is opened each time a text entry is required and closed immediately after writing the text string. When a new selection is started the old file is deleted and a new text file created.

The user can view the contents of the text file by clicking the **Decision Info** button on the results screen of the selection system. Figure 7.3.2.1 shows the information window and the decision information window. As with the results window the user is able to print out the contents of the decision information window if required.

![The Decision Information Window](image)

Figure 7.3.2.1. The Decision Information Window.
7.4 Evaluation

From the trials it can be seen that the system has, on the whole, met the aims stated in Chapter 3.2: System Requirements.

There was strong agreement from the expert users that there was a need for such a system. It could be viewed that experts may feel that such design advice systems undermine their value. However, in this case the expert operated rapid prototyping services on a commercial basis and the money they make comes from the services they provide to industry. Therefore, they had the view that anything that could aid potential customer’s understanding of rapid prototyping could only lead to a better level of service. The possibility of attracting customers previously discouraged through poor understanding was also noted. In addition, there was strong agreement that the system methodology was valid and successful in achieving the aims of the system.

User Input and Control

The fact that users with no prior knowledge of the system could successfully run a solution indicated that the graphical user interface was simple and effective. The users required no training and operated the system by following the instructions and guidelines accessed through the “Help” buttons. Indeed, some users felt they did not need some of the help screens. As few inputs are required none of the users felt that system was too slow or laborious to use. All of the users either knew values for the required inputs or had them readily to hand.

Areas where the trial users felt the system could be improved have been addressed to some degree. See Chapter 7.3: Reaction to the Trial Results. In addition, other areas where the system could be improved have been investigated and are discussed in Chapter 8: Discussion and Further Work.
Processing

Once all of the inputs have been entered the time required for the system to process the solution is almost instantaneous. However, the time required to analyse the STL file was longer, although none of the users felt that this was an unacceptable delay. Analysis time for STL files varied from a few seconds to a little over two minutes for a 66K file. This corresponds to a file containing about 1300 facets which approaches the matrix size limit of this research system. A timed query involving full use of all of the help screens and explanation material took just under eight minutes. Once users were familiar with the system query times fell to a few minutes. From this it can be seen that even for a product assembly consisting of many components a user can perform a full query in less than an hour.

Results

The results were well presented for the majority of users. Some who may have been unsure of the processes being recommended made use of the “More Info” buttons to access descriptions and explanations.

The majority of users felt that the estimates seemed reasonable and would have a degree of faith in them. Most felt that they would be in a much better position to seek a quotation from a service provider after using the system.

Education

The system was successful in educating the user in the operation of the system and no problems were encountered in that respect. With respect to the rapid prototyping and tooling processes, most users made use of the explanation and descriptive material at least once. Where it was used, it was found to be of an acceptable level. Users commented that they were more comfortable discussing matters with services providers when they had an understanding of the rapid prototyping and tooling processes in question.
Access

This research system was not very portable and all of the trials were carried out using the same computer which had to be moved to each location. In addition the use of two pieces of software, although automated, made transfer of the system to other computers more difficult. Due to the manner in which it has been constructed the software solution used for this research system would not be suitable for widespread distribution. Ways of addressing issues relating to user access are discussed in Chapter 8: Discussion and Further Work.

Updating

As the processes contained in the system are held as a rank list according to a small number of key characteristics, updating the system would simply require the assessment of any new process with regard to these characteristics and placement in the rank list accordingly.

Although this type of updating may be simple, to eliminate potential errors, it should remain the job of the system authors. The practicalities of how this could be achieved would depend upon who is responsible for the upkeep of the design advice system and how it is delivered to the user. This matter is also discussed in Chapter 8: Discussion and Further Work.
8.1 Discussion

At the beginning of this study, through direct experience, the author in agreement with colleagues involved in Rapid Prototyping and design advice became aware that there was a need in industry for education and advice concerning Rapid Prototyping techniques. This need was found to be greatest amongst small companies which accounted for a high proportion of the local industry (South Wales). A thorough review was conducted into rapid prototyping technologies and their practical application during which this need became even more apparent.

There was, therefore, an opportunity to address this need by allowing persons in small companies access to expert advice and knowledge in a rapid, convenient and practical manner. Such expert advice and knowledge could be supplied to a large audience in the form of computer software. This study aimed to assess the feasibility of creating a computer based design advice system that could guide users from small companies through the implementation of rapid prototyping and tooling.

Careful thought was given to the way the software should operate in order to minimise complexity. The overriding factors governing the suitability of rapid prototyping processes for a given object were identified and prioritised. The number of factors that had to manually input by the user were minimised and the results specified in the most suitable manner. To minimise effort for the user, information regarding the object was to be derived from Computer Aided Design (CAD) data wherever possible. This approach assumed that the target user (small company) had access to CAD. However, as CAD data is a pre-requisite for all rapid prototyping systems this was considered a practical approach. The falling cost of both hardware and software means that an increasing number of small firms are investing in 3D CAD, and the use of other technologies that stem from the availability of CAD data, such as Finite Element Analysis, can also increase the small firm's competitiveness.
Once the approach was established a working system was created and developed in a manner that was both rapid and efficient. Previous attempts at creating rapid prototyping selection software used relational databases to weigh up all of the different capabilities of a range of RP systems and compared them with a defined set of desired criteria. One approach concentrated on defining material properties and another sought to create a catalogue of design features. Both approaches required a great deal of data input firstly to create the system but also to generate each solution. These systems required the user to input a large number of very specific properties each of which would be compared to the RP properties in the relational database.

It was felt that these systems were not developed with the needs of small companies in mind, as the level of knowledge required to implement them was beyond the scope that would be expected from the staff of an SME. The nature of the required user input was also felt to be complex and time consuming. In addition the manner in which the results were presented required a high degree of knowledge to interpret.

In contrast, the system described here required the minimum possible number of user inputs and applied decision rules that successively eliminated alternatives routes according to prioritised criteria. This approach resulted in simpler coding that operated quickly and presented the user with recommendations as opposed to the previous work which presented the user with comparative scores for all possible routes.

**Development Issues**

Development time was reduced by using separate ‘off the shelf’ programming environments. One enabled the production of the core functionality, program control and graphical user interface. The other was used to read in binary CAD data and derive useful information from it. The two elements were combined, using inter-application communication software, to appear to the user as a single application.
Unlike the previous work the prototype software resulting from this investigation was trialled by target users and experts and found to be successful, within the constraints of the study. Expert opinion was found to be in agreement with the general approach of the system, its operation and perhaps most importantly the need for such a system in industry. Feedback from target users suggested that the system met their needs in all of the most important respects. In more general terms most of the trial users expressed the opinion that such a system would prove useful to small companies involved with product development. The areas where trial users felt the system to be deficient could be successfully addressed with further development, perhaps leading to a commercially viable product.

The end result of the study is a programming approach and set of relatively simple software rules that can hold and disseminate design advice on the subject of rapid prototyping to small companies in a rapid and convenient manner. Although the facilities used to realise and develop these rules may not be suitable for publication in large volumes they should be easily transferable to other more suitable software environments, such as the Internet.

State of the Industry Issues

When the previous work was undertaken, and this study began, RP was still a relatively new and exciting, if unproven, area of product development. The machines were rare, expensive and required practice and expertise to operate. Driven by the need to reduce development schedules, manufacturing industry was highly interested but largely unaware of the capabilities of the various systems. This was an issue complicated by the rapid improvements being made by the RP machine developers. The previous RP selection work, like much of the research conducted at the time was undertaken by manufacturing engineers and scientists and consequently seemed to be aimed at the knowledgeable community, mostly researchers based within universities or companies large enough to devote R&D resources to the perfection of RP. In marked contrast this study was undertaken from a design perspective with a particular
emphasis placed on the needs of small companies.

Since then the RP industry has developed and matured incredibly quickly. Stereolithography in particular is now considered standard practice for many companies. The emphasis of research, primarily driven by large companies, has now moved to the investigation of faster methods of creating high volume tooling. The audience initially interested in RP process capabilities and their selection is now more or less knowledgeable. The fact that most of the common RP processes seem to have levelled out at an economic balance between capability goals and running costs also means that the area of RP capability assessment is now not of high interest. However, there still remains the small manufacturing company, a great number of whom have yet to embrace the benefits of 3D CAD let alone the use of follow on processes such as Rapid Prototyping. Many of these companies still have not gained a working knowledge of the opportunities available. In the near future it is likely that small companies are increasingly likely to invest in 3D CAD as the costs of both hardware and software falls, and consequently they may develop a keener interest in RP. This study has therefore remained of great relevance to its target user throughout this period whilst the general excitement over RP in major industry has died down.

From the trials it was also suggested that a system such as the one described in this study could prove useful to companies already familiar with RP. Such a system could form part of project budgeting procedures allowing the company to estimate a development budget before communicating with external suppliers.

The success of this approach to the development of design advice software for SMEs could be applied to many other areas. Perhaps the most obvious application would be a manufacturing process selection system. The approach of selecting processes according to prioritised characteristics of the component and anticipated manufacturing volumes could be successfully applied to the selection of manufacturing processes. Although the scope of such a system would be massive it
could be broken down into modules for specific industries or market sectors. In addition the approach of successively eliminating unsuitable processes may lead towards solutions rather than attempting to obtain a definitive result from such a wide range of possibilities.

Other issues which could be approached in this manner could include the selections of materials, standard components, electrical components or packaging.

There are of course deficiencies associated with the system described here which are discussed in the following Chapter.
8.2 Further Development of the RP Selection System

The previous Chapters describe how a rapid prototyping and tooling design advice system has been constructed. Of course, now that the main principles are established, the system should be improved and developed to the level where it could be disseminated to the target users as a usable product.

This would require:

- Getting more information about the object into the system in a useful way
- Improving the rules which identify the optimum routes
- Improving and updating the calculations relating to cost and lead time
- Expanding and updating the knowledge-base of available processes and materials

8.2.1 Improving the data derived from the STL file format

“STL is a simple, easy to write format that can produce great results. Its not the most efficient but it works and because so many people have adopted it as a standard it will not be replaced for a number of years.”


As the STL file format is likely to remain the de-facto standard for the transfer of CAD data to RP for the foreseeable future, there is certainly promise for the future of this type of advice system. The similarity of its triangular faceted format to other file types such as VRML, Open Inventor and many three dimensional surface scanners will also provide argument for maintaining its implementation in RP.

It is important to maintain a balance when considering how much information is required from the STL file format. An accurate definition of the key features of an object which affect the selection of rapid prototyping and tooling methods will lead to a more accurate selection procedure. However, this is likely to incur an increase in program complexity and processing time. Inevitably, the law of diminishing returns
will lead to an increasingly small incremental improvement in the selection procedure with each additional piece of information.

As has been described, the derivation of information from the slices taken through the STL file could be enhanced by simply taking more slices. The effective limit on the number of slices will depend mainly on the processing power of the computer being used. The current system takes five slices. A system which takes 20 slices should show an increase in the accuracy of the data. However, a further increase to 50 slices, for example, would probably only show a very small incremental increase in the accuracy of the data, whilst more than doubling the processing time.

To further eliminate the user inputs required by the system, it would be desirable to automatically identify the minimum wall thickness of a given object. In practice this would require a considerable amount of programming, and the result would need to be very reliable since this parameter is of key importance when deciding which rapid prototyping process to use.

When considering tooling aspects, the nature of the tools required could be better identified. In simple terms, an injection moulding tool consists of two halves, male and female. If however, a component requires holes parallel to the split line, the tool may require side actions. These add a considerable amount to the production time and cost of tooling. Therefore, if features requiring side actions could be automatically identified, an associated amount could be added to the estimates relating to the production of tooling. This is not a simple matter but could be achieved in an approximate way by analysing the STL file format.

To identify these features, a split plane would have to be designated. The facets of the STL file which are parallel to the split plane (within angular limits) could then be found. Two sets of facets will of course represent the top and bottom surfaces of the object. Therefore, sets of parallel facets in between these extremities could belong to
features requiring side actions. Complications could arise when such features are formed by shut outs. Features formed in this manner could possibly be identified by analysing facet angles, as shut out holes are normally formed at angles around 5°. However, these in themselves would also represent an increase in the complexity of the tool. With time and some experimental work, the identification of such features may become reliable.

8.2.2 Improving the rules and limits of the Selection System

Some processes are omitted from this experimental system due to lack of information or local availability (i.e. within the UK). These omissions should be corrected in due course. The rules governing the selection of the rapid prototyping processes could be improved if more detailed information concerning their capabilities is documented. Throughout this study an attempt has been made to use practical limits gained from experience of the various RP processes, rather than absolute limits quoted in sales literature, and similar information would be desirable for any new or omitted processes which are added to the system.

The RP processes currently omitted include; the Solider system produced by Cubital and Kira's LOM process. There are no Solider machines in the UK and therefore obtaining relevant data was difficult and somewhat redundant since the design advice system is intended for local (UK) users. Although the Kira machine is available in Britain and was observed in operation, the system has not yet been run commercially and practical data is unavailable. Of the systems included in the current software, many have undergone revisions to the machines and the materials they use. As these modifications become the norm and practical data becomes available, they should also be added to the system. In these cases the software rules would only require modification of some key variables.

Likewise, the selection of secondary tooling methods can be improved when further information concerning their successful application is documented. This
would result in more detailed instructions on the handling and processing required to modify the basic processes when necessary. For example, more detailed information concerning the practical application of Selective Laser Sintered tools would be desirable.

Improvements to the costing routines can be made when more information is available from the STL file and also from ongoing investigation into current practise in the field of RP&T. This would involve investigating the quotation procedures of RP service providers. Increasing markets and competitive forces amongst the service providers will require regular observation to maintain accurate estimations.

8.2.3 Improving User Access to the System

One of the major issues involved in the successful implementation of a design advice system is user access. Alternative methods of delivering the design advice system to the user should be investigated. Of major importance here is the consideration of who would be responsible for delivering and maintaining the design advice system.

Using the Internet to Serve Expert System Software

The system described in this thesis intends to assess the viability of software designed to aid and educate employees in small companies. Because the software has been produced for the purposes of research it is, in its current form, limited in its application and access. However, for such a system to be practical for small companies to use, a greater level of access would be required. If we imagine that the target user is employed by a small manufacturing company, in a region such as Wales, resources will be limited and communications problematic.

The Internet could prove a satisfactory method of serving the system regardless of geography. Many of the issues relating to how this could be achieved depend upon who is serving the software. Such a system could be delivered by a governmental
organisation such as the Department for Trade and Industry, independent advisory services such as the Design Council or an RP service provider. Commercial service providers may however only be inclined to deliver information covering their own services and a certain amount of bias is likely to be encountered.

There are many advantages to running the system on the internet, although the geometry input problem is the same as using a standalone application. Updating the information in the system would be much easier and could be done regularly by the server without hindrance to the user. There is also the possibility that if the application were served from RP service providers their calculations for cost and lead time could be exact and therefore considered as an official estimate. Additional factors could also be included, such as the company's current capacity. Communication via the internet could cater for further advantages, particularly if the company serving the software allowed the system to be used as a method of quotation or means of order and payment.

Further advantages include the fact that internet applications are independent of platform or operating systems. With the advent of VRML allowing 3D web applications, it is feasible that viewing and orientation of the CAD model could be achieved within an internet application. Because VRML is a triangulated model similar in construction to STL files, simple translators could be written to convert one to the other. This allows STL file to be maintained as the object description.

8.2.4 Adding functionality and convenience

In addition to the basic functions, possibilities for further improvements remain feasible. If, for example, the system was served over the internet by a service provider, company specific information (direct ordering information, delivery times etc.) could be detailed. Likewise, the possibilities of email and web links would mean rapid, direct contact with RP manufacturers and suppliers, simplifying consumer liaisons.
The existing design advice system allows the user to print out the results but it may be desirable to have the system compile a full report. This could form part of a product development proposal, budget request or procedural record as part of a quality control routine, such as ISO 9000. The report could be formatted to match the users requirements, detailing the prototyping route, costs, lead times as well as descriptions of the processes to be used and a list of possible service providers.

8.2.5 Adding greater material and process capability

For reasons stated previously, the current experimental system is limited to components intended to be injection moulded in thermoplastics. Expansion or modularization could provide useful design advice on the prototyping of products using other materials and various manufacturing processes.

Additional Moulding Processes

Initially, more thermoplastic materials could be added to the system, allowing more detailed selection of the intended production material. This could include, for example, the specification of thermoplastics with varying degrees of glass filling. It would be relatively simple to expand on the current system to cater for this.

The system could also be expanded to include components intended for volume manufacture using similar moulding techniques, such as, Reaction Injection Moulding (RIM), Compression Moulding or Rotational Moulding. Further developments would also allow the inclusion of components intended to be produced by other less similar moulding processes, such as, Vacuum Forming, Blow Moulding or Contact Moulding (lay up).

Metal and Alloy Components

As was investigated at the beginning of this study a system could be created to cater for components intended to be produced in metal and alloy materials. This may well require a slightly different structure than that of the existing system but many
aspects of the methodology, especially the selection of the rapid prototyping processes, would be directly applicable.

For metal parts, as with the existing system, firstly master patterns are created using rapid prototyping techniques which are then used for the production of suitable prototypes via secondary processes. Likewise the secondary process used will be determined by the number of parts required. The processes have inherent lifespans and capabilities and these could be arranged into rank lists using the methods previously described. See Figures 8.2.5.1. These in combination with the existing selection procedures for rapid prototyping techniques could provide the basis of a selection system for prototype production of metal parts. In addition the accuracy and minimum wall thickness characteristics of the casting processes would need to be considered, examples of which are shown in Figure 8.2.5.2.

With the addition of these capabilities a global system could be created which would offer prototyping solutions for the majority of products, materials and manufacturing processes. Alternatively versions could be created to cater for particular materials or industries.
Figure 8.2.5.1. Metal prototyping processes.

Investment Casting
Accuracy
+/- 0.125mm (over 25mm)

Minimum Wall Thickness
2.00mm for Aluminium
2.25mm for Carbon Steel

Sand Casting
Accuracy
+/- 0.75mm

Minimum Wall Thickness
3.0mm for Aluminium
2.5mm for Brass / Bronze
3.0mm for Cast Iron
5.0mm for Steel

Figure 8.2.5.2. Some casting considerations.
8.2.6 Improving the definition of prototype use

The current classification procedure should be expanded, allowing more specific properties or requirements to be selected by the user. This would be increasingly important if the system was developed to include many more materials and manufacturing processes.

Rather than burden the user with the need to specify physical properties, the current system's categories could be expanded, enabling the user to rapidly hone in on their requirements. This would not necessarily require a detailed knowledge of the parameters or test material properties. For example, as in the current system an intended production material would be specified. Further categories of prototype use could then allow the user to select which material property is most significant. The system could then recommend processes and materials most closely matching the specified property of the intended production material.

In general, the most important characteristic will be stiffness and this assumption is made in the current system. However, other properties may provide the overriding reason for choosing a material such as, tensile strength, shear strength, density, glass transition temperature, melting point, flame retardant, chemical resistance or dialectic strength.
8.3 Recommendations for Future Work

- Develop automatic recognition of appropriate geometric features from the STL file, such as; minimum wall thickness.

- Develop the rules relating to prototyping metal components.

- Improve the user definition or classification of prototype use.

- Investigate which method of delivery best answers the needs of small companies and who would be responsible for its upkeep.

- Create a full system in a native programming environment suitable for delivery in the manner identified.
8.4 Conclusion

This study aimed to establish whether it was feasible and practical to create an automated design advice system capable of successfully guiding small manufacturing companies through the selection and implementation of rapid prototyping and tooling technologies.

The study necessitated a thorough investigation and assessment of the physical properties and capabilities of rapid prototyping and tooling (RP&T) methods and applications. These methods were categorised and arranged according to their capability and suitability for given prototyping applications. The associated costs and lead times were also investigated, leading to the creation of mathematical rules which enabled the practical and reliable estimation of such, for the purposes of advice relating to production planning and budgeting.

Mathematical rules were created to automatically generate the geometric information required by the system relating to the object being prototyped. This information was derived directly from three dimensional computer aided design data.

The result of the study was the combination of these categories, arrangements and mathematical rules into an integrated computer based design advice system. The design, interface, operation, control and output of the design advice system was designed specifically to satisfy the requirements of users in small manufacturing companies.

A trial of the resulting system was conducted with target users in small companies. This resulted in some immediate recommendations and changes. The system was evaluated using this trial and by trial with an acknowledged expert in the field. The study concludes with a discussion of the resulting system and how it could be expanded and employed in a widespread manner.
The results of this study have proved that a computer based system which can aid small companies in the selection of rapid prototyping processes is not only feasible but also practical and desirable. The system was well received by the target users and backed up by expert opinion.

The system, as it stands at the end of this research, forms an excellent building block from which a deliverable product could be created. It is hoped that any such product would maintain the unbiased nature of the research by being developed and delivered by an independent organisation. This would provide the maximum benefit to the many small manufacturing companies throughout the UK.
Appendix 1

Matlab Code equivalent for "dumpstl.c"

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© R. Bibb 4/6/98
STL file format courtesy of 3D Systems Inc.
/* Program dumpstl.c
SGI compile: % CC -DSGI -o dumpstl dumpstl.c

This Program is a utility program which dumps out binary stl files.

Author: Chris R. Manners
Date: 04/11/93

STL File Format:
Ascii Header
Number of Triangles 80 bytes
Triangles
Normal Vertex
  i component 4 byte (float)
  j component 4 byte (float)
  k component 4 byte (float)
First Vertex
  x component 4 byte (float)
  y component 4 byte (float)
  z component 4 byte (float)
Second Vertex
  x component 4 byte (float)
  y component 4 byte (float)
  z component 4 byte (float)
Third Vertex
  x component 4 byte (float)
  y component 4 byte (float)
  z component 4 byte (float)
Attribute

STL file size = (number of triangles * 50) + 84;
*/

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#define TRUE 1
#define FALSE 0

const stl_header_size = 80;

typedef struct
{
  float i; float j; float k;
} normal_type;

typedef struct
{
  float x; float y; float z;
} vertex_type;

typedef struct
{
  normal_type normal;
  vertex_type vertex1;
  vertex_type vertex2;
  vertex_type vertex3;
} stl_triangle;

int readAndSwap(char* buffer, int size, int count, FILE* file, unsigned int reverse)
char *s;
int halfsize;
char temp;
int i,j,k,sizeprime;
int n;    /* number of items read */
n=fread(buffer,size,count,file);
if (feof(file))
{
    printf("End of STL File. \n");
    exit(0);
};
if (n != count)
{
    printf("Error reading stl triangle\n");
    exit(2);
}
if (!reverse || n<count || size<2) return n;
halfsize=size>>1;
sizeprime = size-1;    /* move it out of the loop */
s=(char*)buffer;
for (i=0; i<count; i++,s+=size)
{
    for (j=0; j<halfsize; j++)
    {
        k=sizeprime-j;
        temp=s[j];
        s[j]=s[k];
        s[k]=temp;
    }
    return n;
}

float process_stl_tri(FILE* fp, int printTriangles)
{
    int num_read;
    long unsigned int num_triangles;
    unsigned short attrib;
    stl_triangle new_tri;
    float volume;
    volume = (float)0.0;
    #ifdef WIN32
    num_read = readAndSwap((char* )&(num_triangles),4,1,fp,FALSE);
    #else
    num_read = readAndSwap((char* )&(num_triangles),4,1,fp,TRUE);
    #endif
    printf("Number of Triangles: %u
",num_triangles);
    for ( long unsigned int i = 0; i < num_triangles; i++ )
    {
        #ifdef WIN32
        num_read = readAndSwap((char*) &new_tri,4,12,fp,FALSE);
        #else
        num_read = readAndSwap((char*) &new_tri,4,12,fp,TRUE);
        #endif
        if (printTriangles)
        {
            printf("Triangle: %u
",i+1);
            printf(" Normal: %f %f %f\n",new_tri.normal.i,new_tri.normal.j,
                   new_tri.normal.k);
        }
    }

    Code for dumpstl.c. © C. Manners, 3D Systems Inc. 4/11/93  237
void read_stl_header(FILE* fp)
{
    char stl_header[80];
    int num_read;
    num_read = fread(stl_header,1,stl_header_size,fp);
    if (feof(fp))
    {
        printf("End of STL File. \n");
        exit(0);
    }
    if (num_read != stl_header_size)
    {
        printf("Error reading stl header\n");
        exit(2);
    }

    for (int i = 0; i < stl_header_size; i++)
    {
        printf("%c",stl_header[i]);
    }

    // Code for dumpStl.c, © C. Manneta, 3D Systems Inc. 4/17/92
}
void process_stl_file(FILE* pstlfile, int printTriangles)
{
    float volume;
    read_stl_header(pstlfile);
    volume = process_stl_tri(pstlfile, printTriangles);
    printf("\nSTL Volume: %.1f\n", volume);
}

FILE* openStlFile( char* fileName)
{
    FILE* fp;
    if ((fp = fopen(fileName, "rb")) == NULL)
    {
        printf("Unable Open File: %s\n", fileName);
        exit(1);
    }
    printf("STL file name: %s\n", fileName);
    return(fp);
}

void main(int argc,char **argv)
{
    FILE* pstlfile;
    char filename[64] = "";
    int printTriangles = 1;
    for (int i = 1; i < argc; i++)
    {
        if (!strcmp("-vol", argv[i])) printTriangles = 0;
        else strcpy(filename, argv[i]);
    }
    if (!strcmp(filename, ""))
    {
        printf("Enter STL File Name: ");
        scanf("%s", filename);
    }
    pstlfile = openStlFile(filename);
    process_stl_file(pstlfile, printTriangles);
    fclose(pstlfile);
Appendix 2
Code "lpintersec.m"

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© J. Ward 22/7/97
function out=lspintersec(pk,pl,planedef,reportinp)
% LSPINTERSEC returns the coordinates of a line segment's intersection with a plane
%
% out=lspintersec(pk,pl,planedef)
%
% where pk,pl are 3-vectors giving the start and end points of the line seg
% planedef is a 4-vector giving the parameters a,b,c,d of an implicitly
% defined plane (ax+by+cz+d=0)
%
% the function returns an empty matrix if no intersection takes place
% if the line segment lies in the plane it returns the two end points
% otherwise it returns the intersection co-ordinates
%
% © Jonathan Ward 22/07/97

if nargin==3
  reportinp=0;
end

a=planedef(1);
b=planedef(2);
c=planedef(3);
d=planedef(4);

xk=pk(1);
yk=pk(2);
zk=pk(3);
x1=pl(1);
y1=pl(2);
z1=pl(3);

f=x1-xk;
g=y1-yk;
h=z1-zk;

out=[];

denom=a*f+b*g+c*h;
if abs(denom)<eps
  pf=a*x1+b*y1+c*z1+d;
  if (abs(pf)<eps)&&(reportinp==1)
    out=[[xk yk zk;x1 y1 z1]'];
  end
else
  t=-(a*xk+b*yk+c*zk+d)/denom;
  if (t>=0)&&(t<=1)
    x=xk+f*t;
    y=yk+g*t;
    z=zk+h*t;
    out=[x y z]';
  end
end
Appendix 3
Matlab Code "csarea.m"

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© R. Bibb 4/6/98
function jwout=csarea(stldata,zlevel)
% csarea.m takes a slice out of an stl file and will calculate perimeter
% and cross sectional area
% does not plot result, is called from compslice.m
% out=myslice(stldata,zlevel)
% stldata must be an n x 12 matrix, as provided by readstl
% zlevel is the z value at which the slice is to be taken
% the output matrix has one row for each triangle that intersects
% zlevel.
% Each row is of the form
% [i j xs ys xf yf original_triangle_number]
% The normals have NOT been normalised (ie the sum of their squares will
% not be 1).
% @Jonathan Ward 22/07/97 modified by Richard Bibb 26/9/97
% first define the plane
% ax+by+cz+d=0
% we are using a z=level plane, so
a=0;
b=0;
c=1;
d=-zlevel;
bigout=[];
for tri=1:size(stldata,1)
    out=[];
side=1;
    out1=[ lspintersec(stldata(tri,4:6)','stldata(tri,7:9)',[a b c d])];
side=2;
    out2=[ lspintersec(stldata(tri,7:9)',stldata(tri,10:12)',[a b c d])];
side=3;
    out3=[ lspintersec(stldata(tri,10:12)',stldata(tri,4:6)',[a b c d])];
    out=[out1 out2 out3];
    if ~isempty(out)
        %line('xdata',out(1,:), 'ydata',out(2,:), 'zdata',out(3,:));
        bigout=[bigout; tri reshape(out, 1,6)];
    end
end

%now add normals

bigout2=[];
for ln=1:size(bigout,1)
    bigout2=[bigout2; stldata(bigout(ln,1),1:2) bigout(ln,[2:3 5:6]) bigout(ln,1)];
end
sb=size(bigout2,1);

bba=0;
for j=1:size(bigout2,1)
    minx=min(min(bigout2(:,[3 5])));
    maxx=max(max(bigout2(:,[3 5])));
    miny=min(min(bigout2(:,[4 6])));
    maxy=max(max(bigout2(:,[4 6])));
    bba=(maxy-miny) * (maxy-miny);

end

Matlab code “csarea.m”
peri=0;
for j=1:size(bigout2,1)
na=(bigout2(j,1));
nb=(bigout2(j,2));

xk=(bigout2(j,3));
yk=(bigout2(j,4));
xl=(bigout2(j,5));
yl=(bigout2(j,6));
xlk=xl-xk;
ylk=yl-yk;
rsq=(xlk*xlk)+(ylk*ylk);
length=sqrt(rsq);
peri=peri+length;
end
csarea=0;
negarea=0;
posarea=0;
for j=1:size(bigout2,1)
na=(bigout2(j,1));
nb=(bigout2(j,2));
if nb<0
x1=(bigout2(j,3));
y1=(bigout2(j,4));
xm=(bigout2(j,5));
ym=(bigout2(j,6));
aone=((xm-xl)*(ym-y1))*0.5;
atwo=((xm-xl)*yl);
negarea=negarea+abs(aone)+abs(atwo);
else
x1=(bigout2(j,3));
y1=(bigout2(j,4));
xm=(bigout2(j,5));
ym=(bigout2(j,6));
aone=((xm-xl)*(ym-y1))*0.5;
atwo=((xm-xl)*yl);
posarea=posarea+abs(aone)+abs(atwo);
end
csarea=posarea-negarea;
end
wall=sqrt(csarea);
sa=['The perimeter is ' num2str(peri) '.'];
sc=['The number of lines is ' num2str(sb) '.'];
disp(sc);
disp(sa);
da=['The cross sectional area is ' num2str(csarea) '.'];
disp(da);
db=['The bound slice area is ' num2str(bba) '.'];
disp(db);
ratio=(csarea/bba)*100;
dc=['The ratio of cross sectional area to bound area is ' num2str(ratio) '.'];
disp(dc);
dd=['The square root of the cross sectional area is ' num2str(wall) '.'];
disp(dd);
jwout=[sb peri csarea bba ratio wall];
%output properties
Appendix 4
Matlab Code “compslice.m”

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© R. Bibb 4/6/98
function alldata=compslice(filename)
% Copyright Richard Bibb 4/6/98
% compslice.m reads an stl file shows it and calculates surface area,
%volume and calls csarea.m at five z levels
fid=fopen(filename,'r','l'); %opens the stl file with read only permission
%and ieee floating point with little-endian byte ordering
%read header
header=fread(fid,80,'char'); %reads files header, i.e. stl file title
s=char(header); %prints title
r=['The stl file header reads -- '(s).' ];
disp(r)
num_tri=fread(fid,1,'int32'); %reads and prints the number of triangles
num_tris=num2str(num_tri); %prints title
t=num2str(num_tris);
disp(t)
siz=(num_tri*50)+84; %prints title
f=['The file size in bytes is ' num2str(siz)];
disp(f)
g=['All dimensions are in millimetres'];
disp(g)
clf

set(gcf,'Position',[650 690 470 465]) %calls vcons.m view control program
vcons;
set(gca,'DataAspectRatio',[1 1 1]) %fixes proportions
set(gca,'xgrid','on') %grid on
set(gca,'ygrid','on') %puts stl header name in figure
set(gca,'zgrid','on') %light position
set(gca,'title','text(0,0,(filename))') %material property
light('Position',[140 25 5]) %three dimensional isometric view
material shiny
view(3)

alldata=[];
j=1;
while feof(fid)==0 %empty matrix alldata
  data=fread(fid,12,'float32'); %x data
  att=fread(fid,1,'int16'); %y data
  if feof(fid)==0 %z data
    p(j)=patch;
    set(p(j), 'xdata', data(4) data(7) data(10) , ... %shading property
     'ydata', data(5) data(8) data(11) , ... %face colour, grey
     'zdata', data(6) data(9) data(12) , ... %eliminates edge lines
     'facelighting', 'phong', ... %back lighting
     'facecolor', [0.5 0.5 0.5], ... %reflectivity properties
     'edgecolor', 'none', ... %increment counter
     'backfacelighting', 'lit', ... %close file
     'specularexponent', 5 , ... %finds extents
     'specularcolorreflectance', 0.5 , ... %xmin=min(min(alldata(:, [4 7 10])));
     'diffusestrength', 0.75 , ... %xmax=max(max(alldata(:, [4 7 10])));
     'specularstrength', 1 );
  end
  j=j+1;
end
%disp(alldata)
fclose(fid);
xmin=min(min(alldata(:, [4 7 10])));
xmax=max(max(alldata(:, [4 7 10])));
Matlab code "compslice.m"
ymin=min(min(alldata(:,[5 8 11])));  %shows extents
ymax=max(max(alldata(:,[5 8 11])));
zmin=min(min(alldata(:,[6 9 12])));
zmax=max(max(alldata(:,[6 9 12])));
xext=[(xmin), (xmax)];  %level of first slice
yext=[(ymin), (ymax)];  %level of second slice
zext=[(zmin), (zmax)];  %level of third slice
xsize=xmax-xmin;
ysize=ymax-ymin;
zsize=zmax-zmin;
cut1=0.01*zmin;  %level of fourth slice
cut2=0.1*zmin;  %level of fifth slice
cut3=0.25*zmin;
cut4=0.5*zmin;
cut5=0.75*zmin;
cut6=0.99*zmin;
xext=[The extents in x are'];
disp(xext)
yext=[The extents in y are'];
disp(yext)
zext=[The extents in z are'];
disp(zext)
xcen=((xmax-xmin)/2)+xmin;  %finds centre of extents
ycen=((ymax-ymin)/2)+ymin;
zcen=((zmax-zmin)/2)+zmin;
cent=[(xcen), (ycen), (zcen)];
exn=[The centre of extents is'];
disp(exn)

area=0;
for n=1:num_tri  %set area to zero
    xk=alldata(n,4);
yk=alldata(n,5);
zk=alldata(n,6);
xl=alldata(n,7);
yl=alldata(n,8);
zl=alldata(n,9);
xm=alldata(n,10);
ym=alldata(n,11);
zm=alldata(n,12);
al1=(yl-yk)*(zm-zk)-(zl-zk)*(ym-yk);
b1l=(zl-zk)*(xm-xk)-(xl-xk)*(zm-zk);
c1l=(xl-xk)*(ym-yk)-(yl-yk)*(xm-xk);
aline=al1^2;
bline=b1l^2;
cline=c1l^2;
al=0.5*[(aline+bline+cline)^0.5];
area=area+al;
end
pa=[The surface area is 'num2str(area)' ];  %displays the area
disp(pa)

vol=0;
for n=1:num_tri
    aa=alldata(n,4);
end  %set volume to zero

Matlab code "compelie.its"
%each triangle using the origin as the fourth point

\begin{verbatim}
ab = (ndata(n,8));
ac = (ndata(n,12));
a = aa*ab*ac;

ba = (ndata(n,5));
bb = (ndata(n,9));
bc = (ndata(n,10));
b = ba*bb*bc;

cb = (ndata(n,7));
cc = (ndata(n,11));
c = ca*cb*cc;

da = (ndata(n,6));
db = (ndata(n,8));
dc = (ndata(n,10));
d = da*db*dc;

ea = (ndata(n,5));
eb = (ndata(n,7));
ec = (ndata(n,12));
e = ea*eb*ec;

fa = (ndata(n,4));
fb = (ndata(n,9));
fc = (ndata(n,11));
f = fa*fb*fc;

vol = vol + ((a+b+c-d-e-f)/6);
end

pv = ['The part volume is ' num2str(vol) '.'];
disp(pv)

bbv = (xmax-xmin)*(ymax-ymin)*(zmax-zmin);

pb = ['The bounding box volume is ' num2str(bbv) '.'];
disp(pb)

blk = (vol/bbv)*100;

pk = ['The bulk as a percentage is ' num2str(blk) '.'];
disp(pk)

thk = 6*(vol/area);

pl = ['The ratio of volume to surface area multiplied by 6 is ' num2str(thk) '.'];
disp(pl)

j1=csarea(alldata,cut1);
j2=csarea(alldata,cut2);
j3=csarea(alldata,cut3);
j4=csarea(alldata,cut4);
j5=csarea(alldata,cut5);

res=[xsize ysize zsize vol num_tri xmin xmax ymin ymax zmin zmax xcen ycen zcen area bbv blk thk siz cut1 cut2 cut3 cut4 cut5 j1 j2 j3 j4 j5];

name=[filename,'.ret'];
cd 'Macintosh HD:SuperCard 3.0 Folder';
open(name,'w');
count=fprintf(fid,'%6.4f%%',res);
fclose(fid);
\end{verbatim}
Appendix 5
SuperCard Code for "Opener v13"

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on startUp
put empty into cd fld "appScript" of cd "User Inputs" of wd "System"
put empty into cd fld "stl name" of cd "User Inputs" of wd "System"
put empty into cd fld "cadstl" of cd "System Output" of wd "System"
put empty into cd fld "rp method" of cd "System Output" of wd "System"
put empty into cd fld "rp no off" of cd "System Output" of wd "System"
put empty into cd fld "rp cost" of cd "System Output" of wd "System"
put empty into cd fld "machine" of cd "System Output" of wd "System"
put empty into cd fld "rp lead" of cd "System Output" of wd "System"
put empty into cd fld "finishing" of cd "System Output" of wd "System"
put empty into cd fld "finishing cost" of cd "System Output" of wd "System"
put empty into cd fld "secondary tooling" of cd "System Output" of wd "System"
put empty into cd fld "st cost" of cd "System Output" of wd "System"
put empty into cd fld "st lead" of cd "System Output" of wd "System"
put empty into cd fld "st no off" of cd "System Output" of wd "System"
put empty into cd fld "shot cost" of cd "System Output" of wd "System"
put empty into cd fld "st no off lead" of cd "System Output" of wd "System"
put empty into cd fld "max poss" of cd "System Output" of wd "System"
put empty into cd fld "st material" of cd "System Output" of wd "System"
put empty into cd fld "total cost" of cd "System Output" of wd "System"
put empty into cd fld "total lead" of cd "System Output" of wd "System"
put empty into cd fld "rptext" of cd "rinfo" of wd "Information"
put empty into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
end startUp

on openProject
open resources <<< extremely important statement!

-- importExternal "XPCN", "AppleScript" -- used during development

get AppleScript("Open", "AppleScript") -- connect with AppleScript component
if it is not empty then answer it

pass openProject
end openProject

on closeProject
get AppleScript("Close") -- disconnect with AppleScript component
if it is not empty then
answer "Unable to open AppleScript, either because it is not installed," \
&"or because the System partition is unable to grow any larger." with "I'll Check"
end if

close resources
pass closeProject
end closeProject

on first
Global PROTOUSE
second
partSize
howBig
switch
case PROTOUSE ="Not Property Specific"
rpOnly
exit switch
case PROTOUSE ="Physical Property Specific"
mastervacCasting
exit switch
case PROTOUSE ="Production Material Specific"
masterresinPlastic
exit switch
case PROTOUSE ="Production Process Specific"
mastersprayMetal
exit switch
end switch
end first

on second
Global SPECIAL
  if SPECIAL = "Transparent" then
    seeThru
  else
    whichPu
  end if
end second

on howHigh
Global ASPECT
  if ASPECT > 3.9 then
    put "Machine inserts for high aspect ratio features" into cd fld "secondary additional" of cd "System Output" of wd "System"
  else
    put "Not required" into cd fld "secondary additional" of cd "System Output" of wd "System"
  end if
end howHigh

on howBig
Global XEXTENT, YEXTENT, ZEXTENT, MULTIPLE
switch
  case XEXTENT < 55 and YEXTENT < 25 and ZEXTENT < 15
    put 4 into MULTIPLE
  exit switch
  case XEXTENT < 110 and YEXTENT < 50 and ZEXTENT < 30
    put 2 into MULTIPLE
  exit switch
  case XEXTENT > 110 and YEXTENT > 50 and ZEXTENT > 30
    put 1 into MULTIPLE
  exit switch
end switch
end howBig

on rpOnly
Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, BEDAREA
set numberFormat to 0.0000
put XEXTENT * YEXTENT into BEDAREA
put "None Required" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put empty into cd fld "st material" of cd "System Output" of wd "System"
pull NUMREQ into cd fld "rp no off" of cd "System Output" of wd "System"
master
  if NUMREQ < 5 then
    open file "rponlytext"
    read from file "rponlytext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  else
    vacCasting
  end if
end rpOnly

on vacCasting
Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, VACCOST, PUM
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
if XEXTENT > 860 or YEXTENT > 560 or ZEXTENT > 610 then
  resinPu
else
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
  put "20" into cd fld "max poss" of cd "System Output" of wd "System"
  if NUMREQ < 20 then
    put "Vacuum Casting" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put PUM into cd fld "st material" of cd "System Output" of wd "System"
    vacCost
    set numberFormat to 0.00
    put VACCOST into cd fld "st cost" of cd "System Output" of wd "System"
  end if
end vacCasting

put VACCOST/10 into cd fld "shot cost" of cd "System Output" of wd "System"
set numFormat to 0.0
put 2.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 6 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "vacCasttext"
read from file "vacCasttext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
else
vacDouble
end if
end vacCasting

on vacDouble
Global NUMREQ, MULTIPLE, RPCOST, VACCOST, XEXTENT, YEXTENT, ZEXTENT, PUM
put "Multiple Master Patterns" into cd fld "rp no off" of cd "System Output" of wd "System"
set numFormat to 0
put NUMREQ / 2 into cd fld "st no off" of cd "System Output" of wd "System"
put '40 parts (20 shots)' into cd fld "max pass" of cd "System Output" of wd "System"
if MULTIPLE = 1 then
resinPu
else
if MULTIPLE = 4 then
vacQuad
else
if NUMREQ <40 then
put "Vacuum Casting - Double Impression" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put PUM into cd fld "st material" of cd "System Output" of wd "System"
put XEXTENT*2 into XEXTENT
put YEXTENT*2 into YEXTENT
put ZEXTENT*2 into ZEXTENT
vacCost
set numFormat to 0.00
put VACCOST into cd fld "st cost" of cd "System Output" of wd "System"
put VACCOST/10 into cd fld "shot cost" of cd "System Output" of wd "System"
set numFormat to 0.0
put 2.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 12 into cd fld "st no off lead" of cd "System Output" of wd "System"
set numFormat to 0.00
put RPCOST*4 into cd fld "rp cost" of cd "System Output" of wd "System"
open file "vacDoubletext"
read from file "vacDoubletext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
else
resinPu
end if
end if
end vacDouble

on vacQuad
Global NUMREQ, MULTIPLE, RPCOST, VACCOST, XEXTENT, YEXTENT, ZEXTENT, PUM
put "Multiple Master Patterns" into cd fld "rp no off" of cd "System Output" of wd "System"
set numFormat to 0
put NUMREQ / 4 into cd fld "st no off" of cd "System Output" of wd "System"
put '80 parts (20 shots)' into cd fld "max pass" of cd "System Output" of wd "System"
if NUMREQ <80 then
put "Vacuum Casting - Quadruple Impression" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put PUM into cd fld "st material" of cd "System Output" of wd "System"
put XEXTENT*4 into XEXTENT
put YEXTENT*4 into YEXTENT
put ZEXTENT*4 into ZEXTENT
vacCost
set numFormat to 0.00
put VACCOST into cd fld "st cost" of cd "System Output" of wd "System"
put VACCOST/10 into cd fld "shot cost" of cd "System Output" of wd "System"
set numFormat to 0.0
put 2.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 24 into cd fld "st no off lead" of cd "System Output" of wd "System"
put RCOST/4 into cd fld "rp cost" of cd "System Output" of wd "System"
open file "vacQuadtext"
read from file "vacQuadtext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
else
  resinPu
end if
end vacQuad

on resinPu
Global NUMREQ, FUM, RESINCOST
set numberFormat to 0.0
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "200" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
if NUMREQ < 200 then
  put "Aluminium Filled Epoxy Tools - Polyurethane" into cd fld "secondary tooling" of cd -"System Output" of wd "System"
  put FUM into cd fld "st material" of cd "System Output" of wd "System"
  resinCost
  set numberFormat to 0.00
  put RESINCOST into cd fld "st cost" of cd "System Output" of wd "System"
  put RESINCOST/30 into cd fld "shot cost" of cd "System Output" of wd "System"
  set numberFormat to 0.0
  put 4.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 6 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "resinPutext"
  read from file "resinPutext" until eof
  put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  close file "resinPutext"
  open file "resinPutwarning"
  read from file "resinPutwarning" until eof
  put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
  close file "resinPutwarning"
else
  sprayMetal
end if
end resinPu

on resinPlastic
Global NUMREQ, MAT, RESINCOST
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "50" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if NUMREQ < 50 then
  put "Aluminium Filled Epoxy Tools - Thermoplastic" into cd fld "secondary tooling" of cd -"System Output" of wd "System"
  resinCost
  set numberFormat to 0.00
  put RESINCOST into cd fld "st cost" of cd "System Output" of wd "System"
  put RESINCOST/50 into cd fld "shot cost" of cd "System Output" of wd "System"
  set numberFormat to 0.0
  put 4.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 6 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "resinPlastictext"
  read from file "resinPlastictext" until eof
  put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  close file "resinPlastictext"
  open file "resinPlasticwarning"
  read from file "resinPlasticwarning" until eof
  put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
  close file "resinPlasticwarning"
else

on directAIM

Global NUMREQ, MAT
put "I Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "200*" into cd fld "max poss" of cd "System Output" of wd "System"
set numberFormat to 0.0
if NUMREQ <200 then
  put "Direct AIM SLA epoxy tool" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
put 2.00 into cd fld "shot cost" of cd "System Output" of wd "System"
put 3.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 100 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "directAIMtext"
read from file "directAIMtext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
close file "directAIMtext"
open file "directAIMwarning"
read from file "directAIMwarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "directAIMwarning"
else
sprayMetal
end if
end directAIM

on sprayMetal

Global NUMREQ, MAT, XEXTENT, YEXTENT, ZEXTENT
put "I Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "200*" into cd fld "max poss" of cd "System Output" of wd "System"
set numberFormat to 0.0000
if XEXTENT <200 or YEXTENT <200 or ZEXTENT <200 then
  put 1250 into cd fld "st cost" of cd "System Output" of wd "System"
else
  put 1750 into cd fld "st cost" of cd "System Output" of wd "System"
end if
set numberFormat to 0.0
if NUMREQ <2000 then
  put "Spray Metal Zinc Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put 1.00 into cd fld "shot cost" of cd "System Output" of wd "System"
put 2.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 100 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "spraytext"
read from file "spraytext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
close file "spraytext"
open file "spraywarning"
read from file "spraywarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "spraywarning"
else
  slstool
end if
end sprayMetal

on slstool

Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, MAT
put "I Verification Part - OPTIONAL" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if XEXTENT <130 and YEXTENT <230 and ZEXTENT <130 and NUMREQ <50000 then
  put "SLS Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
  put 50000 into cd fld "max poses" of cd "System Output" of wd "System"
  put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
  put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
  put 10.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 2000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "slstool"
  read from file "slstool" until eof
  put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  close file "slstool"
else
  keltool
end if
end keltool

on keltool
  Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, MAT
  put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if XEXTENT <130 and YEXTENT <130 and ZEXTENT <130 then
  put "3D Keltool Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
  put "1000000" into cd fld "max poses" of cd "System Output" of wd "System"
  put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
  put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
  put 15.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 2000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "keltooltext"
  read from file "keltooltext" until eof
  put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  close file "keltooltext"
  open file "keltoolwarning"
  read from file "keltoolwarning" until eof
  put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
  close file "keltoolwarning"
else
  electroplateTools
end if
end keltool

on electroplateTools
  Global NUMREQ, MAT
  put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put "5000" into cd fld "max poses" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if NUMREQ <5000 then
  put "Electroplated Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
  put 5000 into cd fld "st cost" of cd "System Output" of wd "System"
  put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
  put 15.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 1000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "electrotext"
  read from file "electrotext" until eof
  put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
  close file "electrotext"
  open file "electrowarning"
  read from file "electrowarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
else
  icCast
end if
electroplateTools
end icCast

on icCast
  Global NUMREQ, MAT
  put 1 "Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
  howHigh
  set numberFormat to 0.0
  if NUMREQ <10000 then
    put "Investment Cast Al tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put 10000 into cd fld "max poss" of cd "System Output" of wd "System"
    put 10000 into cd fld "st cost" of cd "System Output" of wd "System"
    put 0.5 into cd fld "shot cost" of cd "System Output" of wd "System"
    put 25.0 into cd fld "st lead" of cd "System Output" of wd "System"
    put NUMREQ / 20000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
    open file "ICaltext"
    read from file "ICaltext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
    close file "ICaltext"
    open file "ICalwarning"
    read from file "ICalwarning" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
    close file "ICalwarning"
  else
    put "Investment Cast Steel tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put 250000 into cd fld "max poss" of cd "System Output" of wd "System"
    put 15000 into cd fld "st cost" of cd "System Output" of wd "System"
    put 0.5 into cd fld "shot cost" of cd "System Output" of wd "System"
    put 25.0 into cd fld "st lead" of cd "System Output" of wd "System"
    put NUMREQ / 20000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
    open file "ICasteeltext"
    read from file "ICasteeltext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
    close file "ICasteeltext"
    open file "ICasteelwarning"
    read from file "ICasteelwarning" until eof
    put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
    close file "ICasteelwarning"
  end if
electroplateTools
end icCast

on master
  Global MINWALL, ACC, RPCOST, SPECIAL, RPTIME, XEXTENT, YEXTENT, ZEXTENT
  set numberFormat to 0.00
  switch
    case MINWALL >6 and ACC >0.20
      lcmCost
      set numberFormat to 0.0
      put "LCM" into cd fld "rpmethod" of cd "System Output" of wd "System"
      open file "lomtext"
      read from file "lomtext" until eof
      put it into cd fld "rptext" of cd "rpinfo" of wd "Information"
      put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
      put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
      put "Hand finish and seal" into cd fld "finishing" of cd "System Output" of wd "System"
      put 0.5*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
      exit switch
    case ACC <0.1 or MINWALL <0.30
      sICost
      set numberFormat to 0.0
      put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"

256
put "Sanders" into cd fld "rpmethod" of cd "System Output" of wd "System"
open file "sanderstext"
read from file "sanderstext" until eof
put it into cd fld "rpdata" of cd "rpinfo" of wd "Information"
if XEXTENT > 150 or YEXTENT > 150 or ZEXTENT > 150 then
  put "Cut CAD or STL file" into cd fld "cadstl" of cd "System Output" of wd "System"
  put "Build in parts" into cd fld "rpmachine" of cd "System Output" of wd "System"
  put 2.0 into RPTIME
else
  put "YM-6Pro" into cd fld "rpmachine" of cd "System Output" of wd "System"
put "Not required" into cd fld "cadstl" of cd "System Output" of wd "System"
put 1.0 into RPTIME
end if
put 2.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
if SPECIAL = "Transparent" then
  put "Polish gently" into cd fld "finishing" of cd "System Output" of wd "System"
  put 0.5*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
else
  put "Not required" into cd fld "finishing" of cd "System Output" of wd "System"
  put 0 into cd fld "finishing lead" of cd "System Output" of wd "System"
end if
exit switch
case ACC <0.13 or MINWALL <0.6
s1Cost
set numberFormat to 0.0
put "SLA epoxy or SLS TrueForm" into cd fld "rpmethod" of cd "System Output" of wd "System"
open file "slatext"
read from file "slatext" until eof
put it into cd fld "rpdata" of cd "rpinfo" of wd "Information"
put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
if SPECIAL = "Transparent" then
  put "Hand finish & polish highly" into cd fld "finishing" of cd "System Output" of wd "System"
else
  put "Hand finish & polish or grit blast" into cd fld "finishing" of cd "System Output" of wd "System"
end if
exit switch
case ACC S0.5 or MINWALL S2
s1Cost
set numberFormat to 0.0
put "SLA, SLS, FDM" into cd fld "rpmethod" of cd "System Output" of wd "System"
open file "alltext"
read from file "alltext" until eof
put it into cd fld "rpdata" of cd "rpinfo" of wd "Information"
put 1*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
if SPECIAL = "Transparent" then
  put "Hand finish & polish highly" into cd fld "finishing" of cd "System Output" of wd "System"
else
  put "Hand finish & polish or grit blast" into cd fld "finishing" of cd "System Output" of wd "System"
end if
exit switch
case ACC >0.5 or MINWALL >5
lcmCost
set numberFormat to 0.0
put "Actua or Genisys" into cd fld "rpmethod" of cd "System Output" of wd "System"
open file "conceoptext"
read from file "conceoptext" until eof
put it into cd fld "rpdata" of cd "rpinfo" of wd "Information"
put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
put "Hand finish" into cd fld "finishing" of cd "System Output" of wd "System"
put 0.5*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
end switch
put 100*RPTIME into cd fld "finishing cost" of cd "System Output" of wd "System"
end master

on partSize
Global XEXTENT, YEKTENT, ZEXTENT, RPTIME
set numberFormat to 0.0000
if XEXTENT >500 or YEKTENT >500 or ZEXTENT >500 then
put "Cut CAD or STL file" into cd fld "cadstl" of cd "System Output" of wd "System"
put "Build in parts" into cd fld "rpmachine" of cd "System Output" of wd "System"
put 2 into RPTIME
else
put "Any machine" into cd fld "rpmachine" of cd "System Output" of wd "System"
put "Not required" into cd fld "cadstl" of cd "System Output" of wd "System"
put 1 into RPTIME
end if
end partSize

on vacCost
Global XEXTENT, YEKTENT, ZEXTENT, VACSIZE, VACCOST
set numberFormat to 0.00
put (XEXTENT/10)+6 into XEXTENT
put (YEKTENT/10)+6 into YEKTENT
put (ZEXTENT/10)+6 into ZEXTENT
put XEXTENT*YEKTENT*ZEXTENT*1.1 into VACSIZE
put (VACSIZE*0.026)+155 into VACCOST
put the round of VACCOST into VACCOST
end vacCost

on resinCost
Global XEXTENT, YEKTENT, ZEXTENT, VACSIZE, RESINCOST
set numberFormat to 0.00
put (XEXTENT/10)+8 into XEXTENT
put (YEKTENT/10)+8 into YEKTENT
put (ZEXTENT/10)+8 into ZEXTENT
put XEXTENT*YEKTENT*ZEXTENT*1.1 into VACSIZE
put (VACSIZE*0.078)+155 into RESINCOST
put the round of RESINCOST into RESINCOST
end resinCost

on whichPu
Global MAT, PUM
switch
  case MAT ="ABS"
    put "PU 6020, 6090" into PUM
    exit switch
  case MAT ="CAB"
    put "PU 6080" into PUM
    exit switch
  case MAT ="Acrylic"
    put "PU SG100, 6090" into PUM
    exit switch
  case MAT ="Polypropylene"
    put "PU 6020" into PUM
    exit switch
  case MAT ="Polystyrene"
    put "PU 2160, 2170" into PUM
    exit switch
  case MAT ="LDPE"
    put "PU 2140" into PUM
    exit switch
  case MAT ="HDPE"
    put "PU 2150" into PUM
    exit switch
  case MAT ="Polycarbonate"
    put "PU 2140" into PUM
    exit switch
put "PU 6090" into PUM
exit switch
case MAT = "PVC"
  put "PU 8050, 2170" into PUM
  exit switch
case MAT = "Nylon 6-6"
  put "PU SG100, 2170" into PUM
  exit switch
case MAT = "EVA"
  put "PU 2130" into PUM
  exit switch
case MAT = "PET"
  put "PU SG100" into PUM
  exit switch
end switch
end which

on seeThru
Global MAT, PUM
switch
case MAT = "CAB"
  put "Clear PU 6090" into PUM
  exit switch
case MAT = "Acrylic"
  put "Clear PU SG100" into PUM
  exit switch
case MAT = "Polymethylmethacrylate"
  put "Clear PU 6090" into PUM
  exit switch
case MAT = "LDPE"
  put "Clear PU 6090" into PUM
  exit switch
case MAT = "Polycarbonate"
  put "Clear PU 6090" into PUM
  exit switch
case MAT = "PVC"
  put "Clear PU SG100" into PUM
  exit switch
case MAT = "PET"
  put "Clear PU SG100" into PUM
  exit switch
end switch
end seeThru

on sICost
Global RPCOST, LAYERS, TDT, TPT, XEXTENT, YEXTENT, ZEXTENT, MINZ, CUR1, CUR2, CUR3, CUR4, CUR5, JICSAREA, J2CSAREA, J3CSAREA, J4CSAREA, J5CSAREA, RONE, R TWO, RTHTHER, RFOUR, RFIVE, DRAWONE, DRAWTWO, DRAWTHREE, DRAWFOUR, DRAWFIVE, MATCOST, BUILDCOST, SUPP, VOL

put XEXTENT/0.15 into LAYERS
put (CUR1-MINZ)/0.15 into RONE
put (CUR2-CUR1)/0.15 into RTWO
put (CUR3-CUR2)/0.15 into RTHTHER
put (CUR4-CUR3)/0.15 into RFOUR
put (CUR5-CUR4)/0.15 into RFIVE
put ((J1CSAREA*RONE)*0.04)/60 into DRAWONE
put ((J2CSAREA*RTWO)*0.04)/60 into DRAWTWO
put ((J3CSAREA*RTHTHER)*0.04)/60 into DRAWTHREE
put ((J4CSAREA*RFOUR)*0.04)/60 into DRAWFOUR
put ((J5CSAREA*RFIVE)*0.04)/60 into DRAWFIVE
put (DRAWONE + DRAWTWO + DRAWTHREE + DRAWFOUR + DRAWFIVE)/60 into TDT
put (LAYERS*(120/48400/((XEXTENT+10)*(YEXTENT+10)))/3600 into TPT
put 0.31*(XEXTENT*YEXTENT)/3600 into SUPP
put (TPT+TDT+SUPP)*70 into BUILDCOST
put (VOL/982181.8182)*500 into MATCOST
put (MATCOST+BUILDCOST)+30 into RPCOST
put the round of RPCOST into RPCOST

end slCost

on lomCost
  Global RPCOST, LAYERS, XEXTENT, YEEXTENT, ZEXTENT, MINZ, CUT1, CUT2, CUT3, CUT4, CUT5, J1PERI,-
    J2PERI, J3PERI, J4PERI, J5PERI, LAYERS, RONE, RTWO, RTHREE, RFour, RFIVE, DRAWONE, DRAWTWO,-
    DRAWTHREE, DRAWFOUR, DRAWFIVE, TOTALDRAW, MATCOST, BUILDCOST, TOTALCOST
  put (ZEXTENT/0.2032)+10 into LAYERS
  put (CUT1-MINZ)/0.2032 into RONE
  put (CUT2 - CUT1)/0.2032 into RTWO
  put (CUT3 - CUT2)/0.2032 into RTHREE
  put (CUT4 - CUT3)/0.2032 into RFour
  put (CUT5 - CUT4)/0.2032 into RFIVE
  put ((((4*(XEXTENT + YEEXTENT)) + J1PERI)/90) / 60) * RONE into DRAWONE
  put ((((4*(XEXTENT + YEEXTENT)) + J2PERI)/90) / 60) * RTWO into DRAWTWO
  put ((((4*(XEXTENT + YEEXTENT)) + J3PERI)/90) / 60) * RTHREE into DRAWTHREE
  put ((((4*(XEXTENT + YEEXTENT)) + J4PERI)/90) / 60) * RFour into DRAWFOUR
  put ((((4*(XEXTENT + YEEXTENT)) + J5PERI)/90) / 60) * RFIVE into DRAWFIVE
  put (DRAWONE + DRAWTWO + DRAWTHREE + DRAWFOUR + DRAWFIVE)/60 into TOTALDRAW
  put (((XEXTENT + 50)*(LAYERS))/1000)*0.55 into MATCOST
  put ((TOTALDRAW + 1)*50) into BUILDCOST
  put BUILDCOST + MATCOST into RPCOST
  put the round of RPCOST into RPCOST
end lomCost
Appendix 6
User Guide for “Opener v13” Trials

Design Engineering Research Centre

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User Guide for Trials

Before you use the system...

You will need an object to use, this should be in the form of a valid STL file of an object in binary format. The system is intended to be used for plastic injection moulded components. The object should be oriented with the smallest overall dimension parallel to the z axis. The object should also be in the positive octant. The system is designed to cope with objects up to 1 metre cubed in size. The system is limited to STL files with fewer than 1300 facets, this equates to a binary file size of less than 66K.

The STL file should be copied into the folder stlfiles which is located in the Matlab Folder which is located in the folder Macintosh HD.

Using the system

If the system is not open it can be opened by double clicking the icon Opener v12. It is located in the SuperCard 3.0 Folder which is located in the folder Macintosh HD.

If you have not used the system before click the Getting Started button.

If you are stuck at any point click on the help button located nearest to the user input area. Note that all help buttons have a red border. Follow these directions to load your STL file and read in the results of the interrogation. A three dimensional image of the STL file should appear next to the user input window, as shown in the example below. An STL file only has to be processed once. If you wish to run a solution using the same STL file you only need to select it and click the Read in results button.
When you have done this you will need to add values for **The Number Of Prototypes Required**, **Minimum Wall Thickness**, **Maximum Aspect Ratio** and **Accuracy**. A description of these inputs can be found by clicking the **Input Help?** button.

When all these are filled click the arrow button to proceed to the next screen. On this screen you can specify the physical requirements of the prototype and it's material by selecting items from the pick lists. Again clicking the **Help?** button will provide a description of these inputs. When you have made your selections click the arrow button to view the results screen.

The results screen will list all of the methods required to produce the desired prototypes. An estimate of cost and lead time will also be displayed for each step. For a description of the processes can be viewed by clicking on the **More Info?** Buttons.

**When you have finished**

You can print out the results, run another solution or quit the application. Please record any comments you may have by using the questions on the next page as a guide.

**User Response**

Could you please express any comments you may have about the system under the headings below. Some suggestions are listed for each heading.

**Ease of use**

Was the application self explanatory?
Did you feel that there were too many inputs required?
Did you feel that there were too few inputs required?
Did you have the inputs required to hand?
Did you find using the application took too long?
Results

Were the results presented in a clear manner?
Did you feel the results were valid?
Did you find the results useful?

Explanation

Did you find the explanation of the resulting processes satisfactory?
Was there enough information?
Was there too much information?

Bugs

If the system failed, gave error messages or did anything unexpected whilst in use please describe the nature of the fault.
Appendix 7
SuperCard Code for “Tracking Try”

Design Engineering Research Centre

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on startUp
put empty into cd fld "appScript" of cd "User Inputs" of wd "System"
put empty into cd fld "stl name" of cd "User Inputs" of wd "System"
put empty into cd fld "cadstl" of cd "System Output" of wd "System"
put empty into cd fld "rpmethod" of cd "System Output" of wd "System"
put empty into cd fld "rp no off" of cd "System Output" of wd "System"
put empty into cd fld "rp cost" of cd "System Output" of wd "System"
put empty into cd fld "rp machine" of cd "System Output" of wd "System"
put empty into cd fld "rp lead" of cd "System Output" of wd "System"
put empty into cd fld "finishing" of cd "System Output" of wd "System"
put empty into cd fld "finishing cost" of cd "System Output" of wd "System"
put empty into cd fld "secondary tooling" of cd "System Output" of wd "System"
put empty into cd fld "st cost" of cd "System Output" of wd "System"
put empty into cd fld "st lead" of cd "System Output" of wd "System"
put empty into cd fld "st no off" of cd "System Output" of wd "System"
put empty into cd fld "shot cost" of cd "System Output" of wd "System"
put empty into cd fld "st no off lead" of cd "System Output" of wd "System"
put empty into cd fld "max poss" of cd "System Output" of wd "System"
put empty into cd fld "st material" of cd "System Output" of wd "System"
put empty into cd fld "total cost" of cd "System Output" of wd "System"
put empty into cd fld "total lead" of cd "System Output" of wd "System"
put empty into cd fld "rptext" of cd "rpinfo" of wd "Information"
put empty into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
end startUp

on openProject
open resources --<< extremely important statement!

importExternal "XFCN", "AppleScript" -- used during development

get AppleScript( "Open", "AppleScript" ) -- connect with AppleScript component
if it is not empty then answer it

pass openProject
end openProject

on closeProject
get AppleScript( "Close" ) -- disconnect with AppleScript component
if it is not empty then
  answer "Unable to open AppleScript, either because it is not installed, "-&"or because the System partition is unable to grow any larger." with "I’ll Check"
end if

close resources
pass closeProject
end closeProject

on first
Global PROTOUSE
second
partSize
switch
  case PROTOUSE = "Not Property Specific" -- then jump to RP only
    rpOnly
    exit switch
  case PROTOUSE = "Physical Property Specific"
    master
    vacCasting
    exit switch
  case PROTOUSE = "Production Material Specific"
    master
    resinPlastic
    exit switch
  case PROTOUSE = "Production Process Specific"
    master
    sprayMetal
    exit switch
on second
Global SPECIAL
if SPECIAL = "Transparent" then
    seeThru
else
    whichPu
end if
end second

on howHigh
Global ASPECT
if ASPECT > 3.9 then
    put "Machine inserts for high aspect ratio features" into cd fld "secondary additional" of cd "System Output" of wd "System"
    open file "tracking"
    write "As the aspect ratio of some features may exceed 4 to 1 (height to width) machined metal inserts for these features are recommended." after file "tracking"
    close file "tracking"
else
    put "Not required" into cd fld "secondary additional" of cd "System Output" of wd "System"
end if
end howHigh

on rpOnly
Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT
put "None Required" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put empty into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "rp no off" of cd "System Output" of wd "System"
master
if NUMREQ <5 then
    open file "tracking"
    write "As less than five parts are required Rapid Prototyping techniques only are required." after file "tracking"
    close file "tracking"
    open file "rponlytext"
    read from file "rponlytext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
else
    vacCasting
end if
end rpOnly

on vacCasting
Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, VACCOST, PUM
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "20" into cd fld "max poss" of cd "System Output" of wd "System"
if NUMREQ <20 then
    put "Vacuum Casting" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put PUM into cd fld "st material" of cd "System Output" of wd "System"
    vacCost
    set numberFormat to 0.00
    put VACCOST into cd fld "st cost" of cd "System Output" of wd "System"
    put VACCOST/10 into cd fld "shot cost" of cd "System Output" of wd "System"
    set numberFormat to 0.0
    put 2.0 into cd fld "st lead" of cd "System Output" of wd "System"
    put NUMREQ / 6 into cd fld "st no off lead" of cd "System Output" of wd "System"
    open file "tracking"
    write "As less than twenty parts are required vacuum casting is recommended." after file "tracking"
    close file "tracking"
    open file "vacCasttext"
    read from file "vacCasttext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
else
    resinPu
end vacCasting
end if
end vacCasting

on resinPu:
Global NUMREQ, FM, RESINCOST
set numberFormat to 0.0
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "200" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
if NUMREQ <200 then
put "Aluminium Filled Epoxy Tools - Polyurethane" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put FM into cd fld "st material" of cd "System Output" of wd "System"
resinCost
set numberFormat to 0.00
put RESINCOST into cd fld "st cost" of cd "System Output" of wd "System"
put RESINCOST/30 into cd fld "shot cost" of cd "System Output" of wd "System"
set numberFormat to 0.0
put 4.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 6 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "tracking"
write "As less than 200 parts are required aluminium filled epoxy resin tools using FM - resins are recommended." after file "tracking"
close file "tracking"
open file "resinPutext"
read from file "resinPutext" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
close file "resinPutext"
open file "resinPutWarning"
read from file "resinPutWarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "resinPutWarning"
else
sprayMetal
end if
end resinPu

on resinPlastic:
Global NUMREQ, MAT, RESINCOST
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "50" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if NUMREQ <50 then
put "Aluminium Filled Epoxy Tools - Thermoplastic" into cd fld "secondary tooling" of cd "System Output" of wd "System"
resinCost
set numberFormat to 0.00
put RESINCOST into cd fld "st cost" of cd "System Output" of wd "System"
put RESINCOST/50 into cd fld "shot cost" of cd "System Output" of wd "System"
set numberFormat to 0.0
put 4.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 6 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "tracking"
write "As less than 50 parts are required aluminium filled epoxy resin tools using thermoplastics are recommended." after file "tracking"
close file "tracking"
open file "resinPlasticText"
read from file "resinPlasticText" until eof
put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
close file "resinPlasticText"
open file "resinPlasticWarning"
read from file "resinPlasticWarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "resinPlasticWarning"
else

on directAIM
Global NUMREQ, MAT
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "200" into cd fld "max poss" of cd "System Output" of wd "System"
set numberFormat to 0.0
if NUMREQ <200 then
put "Direct AIM SLA epoxy tool" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
put 2.00 into cd fld "shot cost" of cd "System Output" of wd "System"
put 3.0 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 100 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "tracking"
write "As less than 200 parts are required Direct AIM is recommended." after file "tracking"
close file "tracking"
open file "directAIMtext"
read from file "directAIMtext" until eof
put it into cd fld "toolinginfo" of cd "toolinginfo of wd "Information"
close file "directAIMtext"
open file "directAIMwarning"
read from file "directAIMwarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "directAIMwarning"
else
sprayMetal
end if
end directAIM

on sprayMetal
Global NUMREQ, MAT, XEXTENT, YEXTENT, ZEXTENT
put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
put MAT into cd fld "st material" of cd "System Output" of wd "System"
put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
put "2000" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0000
if XEXTENT <200 or YEXTENT <200 or ZEXTENT <200 then
put 1250 into cd fld "st cost" of cd "System Output" of wd "System"
else
put 1750 into cd fld "st cost" of cd "System Output" of wd "System"
end if
set numberFormat to 0.0
if NUMREQ <2000 then
put "Spray Metal Zinc Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
put 1.00 into cd fld "shot cost" of cd "System Output" of wd "System"
put 2.00 into cd fld "st lead" of cd "System Output" of wd "System"
put NUMREQ / 1000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
open file "tracking"
write "As less than 2000 parts are required Spray metal tooling is recommended." after file "tracking"
close file "tracking"
open file "spraytext"
read from file "spraytext" until eof
put it into cd fld "toolinginfo" of cd "toolinginfo of wd "Information"
close file "spraytext"
open file "spraywarning"
read from file "spraywarning" until eof
put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
close file "spraywarning"
else
lstool
end if
end sprayMetal

on slstool
  Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, MAT
  put "1 Verification Part - OPTIONAL" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
  howHigh
  set numberFormat to 0.0
  if XEXTENT <130 and YEXTENT <230 and ZEXTENT <130 and NUMREQ <50000 then
    put "SLS Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put 50000 into cd fld "max poss" of cd "System Output" of wd "System"
    put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
    put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
    put 10.0 into cd fld "st lead" of cd "System Output" of wd "System"
    put NUMREQ / 2000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
    open file "tracking"
    write "As less than 50,000 parts are required SLS Tools are recommended." "
  after file "tracking"
    close file "tracking"
    open file "slstext"
    read from file "slstext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
    close file "slstext"
    open file "slswarning"
    read from file "slswarning" until eof
    put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
    close file "slswarning"
  else
    keltool
  end if
end slstool

on keltool
  Global NUMREQ, XEXTENT, YEXTENT, ZEXTENT, MAT
  put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
  howHigh
  set numberFormat to 0.0
  if XEXTENT <130 and YEXTENT <130 and ZEXTENT <130 then
    put "3D Keltool Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
    put "1000000" into cd fld "max poss" of cd "System Output" of wd "System"
    put 2500 into cd fld "st cost" of cd "System Output" of wd "System"
    put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
    put 15.0 into cd fld "st lead" of cd "System Output" of wd "System"
    put NUMREQ / 2000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
    open file "tracking"
    write "As up to 5000 parts are required and the part is smaller than 130mm in each axis 3D Keltool recommended." "
  after file "tracking"
    close file "tracking"
    open file "keltooltext"
    read from file "keltooltext" until eof
    put it into cd fld "toolingtext" of cd "toolinginfo" of wd "Information"
    close file "keltooltext"
    open file "keltoolwarning"
    read from file "keltoolwarning" until eof
    put it into cd fld "warningtext" of cd "toolinginfo" of wd "Information"
    close file "keltoolwarning"
  else
    electroplateTools
  end if
end keltool

on electroplateTools
  Global NUMREQ, MAT
  put "1 Master Pattern" into cd fld "rp no off" of cd "System Output" of wd "System"
  put MAT into cd fld "st material" of cd "System Output" of wd "System"
  put NUMREQ into cd fld "st no off" of cd "System Output" of wd "System"
  SuperCard Code for Tracking Try, 4A.Bibb, 4/98
put "5000" into cd fld "max poss" of cd "System Output" of wd "System"
howHigh
set numberFormat to 0.0
if NUMREQ <5000 then
  put "Electroplated Tools" into cd fld "secondary tooling" of cd "System Output" of wd "System"
  put 500 into cd fld "st cost" of cd "System Output" of wd "System"
  put 0.50 into cd fld "shot cost" of cd "System Output" of wd "System"
  put 15.0 into cd fld "st lead" of cd "System Output" of wd "System"
  put NUMREQ / 1000 +1 into cd fld "st no off lead" of cd "System Output" of wd "System"
  open file "tracking"
  write "As up to 5000 parts are required and the part is larger than 130mm in either axis -
electroplated tools are recommended." after file "tracking"
  close file "tracking"
  open file "electrotext"
  read from file "electrotext" until eof
  put it into cd fld "toolinginfo" of cd "toolinginfo" of wd "Information"
  close file "electrotext"
  open file "electrowarning"
  read from file "electrowarning" until eof
  put it into cd fld "toolinginfo" of cd "toolinginfo" of wd "Information"
  close file "electrowarning"
else
  icCast
end if
end electroplateTools

on master
  Global MINWALL, ACC, RPCOST, SPECIAL, RPTIME, XEXTENT, YEXTENT, ZEXTENT
  set numberFormat to 0.0
  switch case MINWALL >6 and ACC >0.20
    lomCost
    set numberFormat to 0.0
    put "LOM" into cd fld "rpmethod" of cd "System Output" of wd "System"
    open file "tracking"
    write 'As the wall thickness is greater than 6mm and the accuracy required is less than -
0.2mm LOM is recommended." after file "tracking"
    write return to file "tracking"
    close file "tracking"
    open file "lomtext"
    read from file "lomtext" until eof
    put it into cd fld "rptext" of cd "rpinfo" of wd "Information"
    put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
    put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
    put "Hand finish and seal" into cd fld "finishing" of cd "System Output" of wd "System"
    put 0.5*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
  exit switch
  case ACC <0.1 or MINWALL <0.30
    s1Cost
    set numberFormat to 0.0
    put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
    put "Sanders" into cd fld "rpmethod" of cd "System Output" of wd "System"
    open file "tracking"
    write 'As the wall thickness is less than 0.3mm and the accuracy required is less than -
0.1mm the Sanders process is recommended." after file "tracking"
    write return to file "tracking"
    close file "tracking"
    open file "sanderstext"
    read from file "sanderstext" until eof
    put it into cd fld "rptext" of cd "rpinfo" of wd "Information"
    if XEXTENT >150 or YEXTENT >150 or ZEXTENT >150 then
      put "Cut CAD or STL file into cd fld "cadstl" of cd "System Output" of wd "System"
      put "Build in parts" into cd fld "rpmachine" of cd "System Output" of wd "System"
      put 2.0 into RPTIME
    else
      put "MM-6Pro" into cd fld "rpmachine" of cd "System Output" of wd "System"
      put "Not required" into cd fld "cadstl" of cd "System Output" of wd "System"
      put 1.0 into RPTIME
    end if


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put 2.0*RPTIME into cd fld 'rp lead' of cd "System Output" of wd "System"
if SPECIAL = "Transparent" then
    put "Polish gently" into cd fld "finishing" of cd "System Output" of wd "System"
    put 0.5*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
else
    put "Not required" into cd fld "finishing" of cd "System Output" of wd "System"
    put 0 into cd fld "finishing lead" of cd "System Output" of wd "System"
    put 0 into RPTIME
end if
exit switch

case ACC < 0.13 or MINWALL < 0.6
    slCost
    set numberFormat to 0.0
    put "SLA, SLS or TrueForm" into cd fld "rpmethod" of cd "System Output" of wd "System"
    open file "tracking"
    write "As the wall thickness is less than 0.6mm and the accuracy required is less than
    0.13mm SLA using Epoxy resin or SLS using TrueForm are recommended." after file "tracking"
    write return to file "tracking"
    close file "tracking"
    open file "slatext"
    read from file "slatext" until eof
    put it into cd fld "rpinfo" of cd "Information"
    put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
    put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
    if SPECIAL = "Transparent" then
        put "Hand finish & polish highly" into cd fld "finishing" of cd "System Output" of wd "System"
    else
        put 1.0*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
    end if
    exit switch

case ACC > 0.5 or MINWALL > 0.6
    slCost
    set numberFormat to 0.0
    put "SLA, SLS or TrueForm" into cd fld "rpmethod" of cd "System Output" of wd "System"
    open file "tracking"
    write "As the wall thickness is less than 2mm and the accuracy required is less than
    0.5mm SLA, SLS or TrueForm are recommended." after file "tracking"
    write return to file "tracking"
    close file "tracking"
    open file "alltext"
    read from file "alltext" until eof
    put it into cd fld "rpinfo" of cd "Information"
    put 1.0*RPTIME into cd fld "rp lead" of cd "System Output" of wd "System"
    put RPCOST into cd fld "rp cost" of cd "System Output" of wd "System"
    if SPECIAL = "Transparent" then
        put "Hand finish & polish highly" into cd fld "finishing" of cd "System Output" of wd "System"
    else
        put 1.0*RPTIME into cd fld "finishing lead" of cd "System Output" of wd "System"
    end if
    exit switch

case ACC > 0.5 or MINWALL > 5
    slCost
    set numberFormat to 0.0
    put "Actua or Genisys" into cd fld "rpmethod" of cd "System Output" of wd "System"
    open file "tracking"
    write "As the wall thickness is less than 5mm and the accuracy required is less than
    0.5mm Actua or Genisys processes are recommended." after file "tracking"
    write return to file "tracking"
    close file "tracking"
    open file "concepttext"
    read from file "concepttext" until eof
put it into cd f1d "rptext" of cd "rpinfo" of wd "Information"
put 1.0*RPTIME into cd f1d "rp lead" of cd "System Output" of wd "System"
put RPCOST into cd f1d "rp cost" of cd "System Output" of wd "System"
put "Hand finish" into cd f1d "finishing" of cd "System Output" of wd "System"
put 0.5*RPTIME into cd f1d "finishing lead" of cd "System Output" of wd "System"
exit switch
put 100*RPTIME into cd f1d "finishing cost" of cd "System Output" of wd "System"
end master

on partSize
Global XEXTENT, YEXTENT, ZEXTENT, RPTIME
set numberFormat to 0.0000
if XEXTENT >500 or YEXTENT >500 or ZEXTENT >500 then
put "Cut CAD or STL file" into cd f1d "cadstl" of cd "System Output" of wd "System"
put "Build in parts" into cd f1d "rpmachine" of cd "System Output" of wd "System"
pull 2 into RPTIME
else
put "Any machine" into cd f1d "rpmachine" of cd "System Output" of wd "System"
pull "Not required" into cd f1d "cadstl" of cd "System Output" of wd "System"
pull 1 into RPTIME
end if
end partSize

on vacCost
Global XEXTENT, YEXTENT, ZEXTENT, VACSIZE, VACCOST
set numberFormat to 0.00
pull (XEXTENT/10)+6 into XEXTENT
pull (YEXTENT/10)+6 into YEXTENT
pull (ZEXTENT/10)+6 into ZEXTENT
pull XEXTENT*YEXTENT*ZEXTENT*1.1 into VACSIZE
pull (VACSIZE*0.026)+155 into VACCOST
pull the round value of VACCOST into VACCOST
end vacCost

on resinCost
Global XEXTENT, YEXTENT, ZEXTENT, VACSIZE, RESINCOST
set numberFormat to 0.00
pull (XEXTENT/10)+6 into XEXTENT
pull (YEXTENT/10)+6 into YEXTENT
pull (ZEXTENT/10)+6 into ZEXTENT
pull XEXTENT*YEXTENT*ZEXTENT*1.1 into VACSIZE
pull (VACSIZE*0.078)+155 into RESINCOST
pull the round value of RESINCOST into RESINCOST
end resinCost

on whichPu
Global MAT, PUM
switch
    case MAT ="ABS"
        pull "PU 6020, 6090" into PUM
        exit switch
    case MAT ="CAB"
        pull "PU 6080" into PUM
        exit switch
    case MAT ="Acrylic"
        pull "PU SG100, 6090" into PUM
        exit switch
    case MAT ="Polypropylene"
        pull "PU 6020" into PUM
        exit switch
    case MAT ="Polystyrene"
        pull "PU 2160, 2170" into PUM
        exit switch
    case MAT ="LDPE"
        pull "PU 2140" into PUM
        exit switch
    case MAT ="HDPE"
        pull "PU 2150" into PUM
SuperCard Code for Tracking Try, ©R.Ellis, 4/8/98

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exit switch
case MAT = "Polycarbonate"
    put "PU 6090" into PUM
exit switch
case MAT = "PVC"
    put "PU 8050, 2170" into PUM
exit switch
case MAT = "Nylon 6-6"
    put "PU SG100, 2170" into PUM
exit switch
case MAT = "EVA"
    put "PU 2130" into PUM
exit switch
case MAT = "PET"
    put "PU SG100" into PUM
exit switch
end switch

on seeThru
Global MAT, FUM
switch
case MAT = "CAB"
    put "Clear PU 6090" into PUM
exit switch
case MAT = "Acrylic"
    put "Clear PU SG100" into PUM
exit switch
case MAT = "Polypropylene"
    put "Clear PU 6090" into PUM
exit switch
case MAT = "Polystyrene"
    put "Clear PU SG95" into PUM
exit switch
case MAT = "LDPE"
    put "Clear PU 6090" into PUM
exit switch
case MAT = "Polycarbonate"
    put "Clear PU 6090" into PUM
exit switch
case MAT = "PVC"
    put "Clear PU SG90" into PUM
exit switch
case MAT = "PET"
    put "Clear PU SG100" into PUM
exit switch
end switch
end seeThru

on acCost
Global RPCOST, LAYERS, TDT, TPT, XEXTENT, YEXTENT, ZEXTENT, MINZ, CUT1, CUT2, CUT3, CUT5, J1CSAREA, J2CSAREA, J3CSAREA, J4CSAREA, J5CSAREA, RONE, RTWO, RTHREE, RFOUR, RFIVE, DRAWONE, DRAWTWO, DRAWTHREE, DRAWFOUR, DRAWFIVE, MATCOST, BUILDCOST, SUPP, VOL
put XEXTENT/0.15 into LAYERS
put (CUT1-MINZ)/0.15 into RONE
put (CUT2-CUT1)/0.15 into RTWO
put (CUT3-CUT2)/0.15 into RTHREE
put (CUT4-CUT3)/0.15 into RFOUR
put (CUT5-CUT4)/0.15 into RFIVE
put ((J1CSAREA*RTWO)*0.04)/60 into DRAWONE
put ((J2CSAREA*RTHREE)*0.04)/60 into DRAWTWO
put ((J3CSAREA*RFIVE)*0.04)/60 into DRAWTHREE
put ((J4CSAREA*RFOUR)*0.04)/60 into DRAWFOUR
put ((J5CSAREA*RFIVE)*0.04)/60 into DRAWFIVE
put (DRAWONE + DRAWTWO + DRAWTHREE + DRAWFOUR + DRAWFIVE)/60 into TDT
put (LAYERS*120/(48400/((XEXTENT+10)*2)*(YEXTENT+10)))/3600 into TPT
put 0.31*(XEXTENT*YEXTENT)/3600 into SUPP
put (TPT+TDT+SUPP)*70 into BUILDCOST
put (VOL/982181.8182)*500 into MATCOST


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puts (MATCOST+BUILDCOST)+10 into RPCOST
puts the round of RPCOST into RPCOST
end slCost

on lomCost
Global RPCOST, LAYERS, XEXTENT, YEXTENT, ZEXTENT, MINZ, CUT1, CUT2, CUT3, CUT4, CUT5, J1PERI,-
J2PERI, J3PERI, J4PERI, J5PERI, LAYERS, RONE, RTWO, RTHREE, RFOUR, RFIVE, DRAWONE, DRAWTWO,-
DRAWTHREE, DRAWFOUR, DRAWFIVE, TOTALDRAW, MATCOST, BUILDCOST, TOTALCOST
puts (ZEXTENT/0.2032)+10 into LAYERS
put (CUT1-MINZ)/0.2032 into RONE
put (CUT2 - CUT1)/0.2032 into RTWO
put (CUT3 - CUT2)/0.2032 into RTHREE
put (CUT4 - CUT3)/0.2032 into RFOUR
put (CUT5 - CUT4)/0.2032 into RFIVE
put (((4*(XEXTENT + YEXTENT)) + J1PERI)/90) / 60) * RONE into DRAWONE
put (((4*(XEXTENT + YEXTENT)) + J2PERI)/90) / 60) * RTWO into DRAWTWO
put (((4*(XEXTENT + YEXTENT)) + J3PERI)/90) / 60) * RTHREE into DRAWTHREE
put (((4*(XEXTENT + YEXTENT)) + J4PERI)/90) / 60) * RFOUR into DRAWFOUR
put (((4*(XEXTENT + YEXTENT)) + J5PERI)/90) / 60) * RFIVE into DRAWFIVE
put ((DRAWONE + DRAWTWO + DRAWTHREE + DRAWFOUR + DRAWFIVE)/60 into TOTALDRAW
put (((XEXTENT + 50)*(LAYERS))/1000)^0.55 into MATCOST
put ((TOTALDRAW + 1)*50) into BUILDCOST
put BUILDCOST + MATCOST into RPCOST
puts the round of RPCOST into RPCOST
end lomCost