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Using Feature-based Product Modelling to Integrate Design and Rapid Prototyping

By

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Abstract

Rapid prototyping (RP) provides a means of producing physical models directly from computer aided design (CAD) data. The aim of this research was to determine the most effective method of integrating RP into the design process.

A review of the links between design and RP was undertaken. This revealed that RP is a technology which can benefit several key areas of engineering design. Many computer tools were identified which supported the designer's use of RP but most of these relied on using CAD geometry alone. Using this incomplete set of design information hindered the integration of RP into the design process.

A hypothesis was formulated which stated that a feature-based product modelling methodology was needed to enable RP to become an integrated part of the design process. To demonstrate the validity of the methodology, it was embodied in a design support system (DSS) for rapid prototyping. The DSS requirements were determined through a survey of designers using RP, and a full specification for the system was defined. A demonstration version was implemented using a relational database coupled with a CAD system. The demonstration DSS enabled feature-based geometry and non-geometric information to be integrated within a single product model. An application program was developed which used the product model data to optimise the orientation of an RP model in order to meet the differing surface finish

requirements for each feature in a component. This example use of the system illustrated the benefit of using a feature-based product model to optimise the designer's use of RP.

Future work needed to improve the DSS to a state where it would be ready for development into a commercial package was identified. Finally, conclusions were drawn as to how all the objectives were met and summarising the original contribution to knowledge made by the research.

CONTENTS

CHAPTER FIVE: DEVELOPING THE SPECIFICATION FOR A DESIGN SUPPORT SYSTEM FOR RAPID PROTOTYPING

CHAPTER SIX: DEFINING THE DESIGN SUPPORT SYSTEM FOR RAPID PROTOTYPING

DECLARATION

I declare that this thesis is the result of my own work. It has not, with the exception of Chapter 2, whether in the same or a different form, been presented to this or any other university in support of an application for any degree other than that for which I am now a candidate. As previously declared within my notification of submission, dated 22nd April 1997, Chapter 2 of this thesis contains material which was previously submitted to the University of Warwick as part of a thesis for the degree of Master of Science in Engineering, which I obtained in July 1994.

R. Ian Campbell

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ABBREVIATIONS

2D	two dimensional
3D	three dimensional
ABS	acrylonitrile-butadiene-styrene
ACIS	American committee for inter-operable systems
AP	application protocol
B-rep	boundary representation
BS	British standard
CAD	computer aided design
CADCAM	computer aided design / computer aided manufacturing
CAE	computer aided engineering
CAM	computer aided manufacturing
CAPP	computer aided process planning
CFD	computational fluid dynamics
CNC	computer numerical control
CO^2	carbon dioxide
CSG	constructive solid geometry
DSS	design support system.
EDM	electro-discharge machining
FBD	feature-based design
FDM	fused deposition modeling (US spelling)
FEA	finite element analysis
IGES	initial graphics exchange specification
LOM	laminated object manufacturing
MIT	Massachussets Institute of Technology
MJM	multi-jet modeling (US spelling)
MS	Microsoft
NC	numerical control
PC	personal computer
RDBMS	relational database management system
RP	rapid prototyping
SDM	shape deposition manufacturing
SLA	StereoLithography Apparatus
SLS	selective laser sintering
STEP	STandard for the Exchange of Product data
STL	STereoLithography (exchange file format)
UV	ultra-violet

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CHAPTER ONE

INTRODUCTION

1.1 Background to Project

RP offers tremendous new opportunities to designers in the way of faster realisation of designs and the creation of component shapes that were previously impossible or too expensive to make. It can also revolutionise the design process in that design iterations can be performed more quickly and more often. Several alternative concepts can be created as physical models and evaluated in parallel making it easier to select the optimum design. However, despite these significant benefits to design which can be obtained from using RP, the link between RP and the design process is rather tenuous. This is because most users of RP transfer information to the RP system using the STL file format. This necessitates a precise CAD model, possibly with embedded design intent, to be simplified into a series of triangles which are then transferred to the RP system. The triangles approximate the geometry of the design but contain no other relevant information. This can result in RP models which do not fully meet the designer's requirements, therefore wasting time, money and effort, and leading to disappointment in the RP process.

Therefore, it was decided to investigate the requirement for better integration between design and RP with the aim of optimising the effectiveness of the RP process.

1.2 Research Methodology

The two-phase research methodology followed during this project is illustrated in Figure 1.1. The initial phase of the project involved a general review of literature relating to RP followed by a specific investigation into previous work in the area of linking design and RP. This was achieved through library and database searches including use of the Internet. Conferences which related to this area were also attended. This gave the author the opportunity for discussion with others working in the same field to solicit their views on the proposed research project.

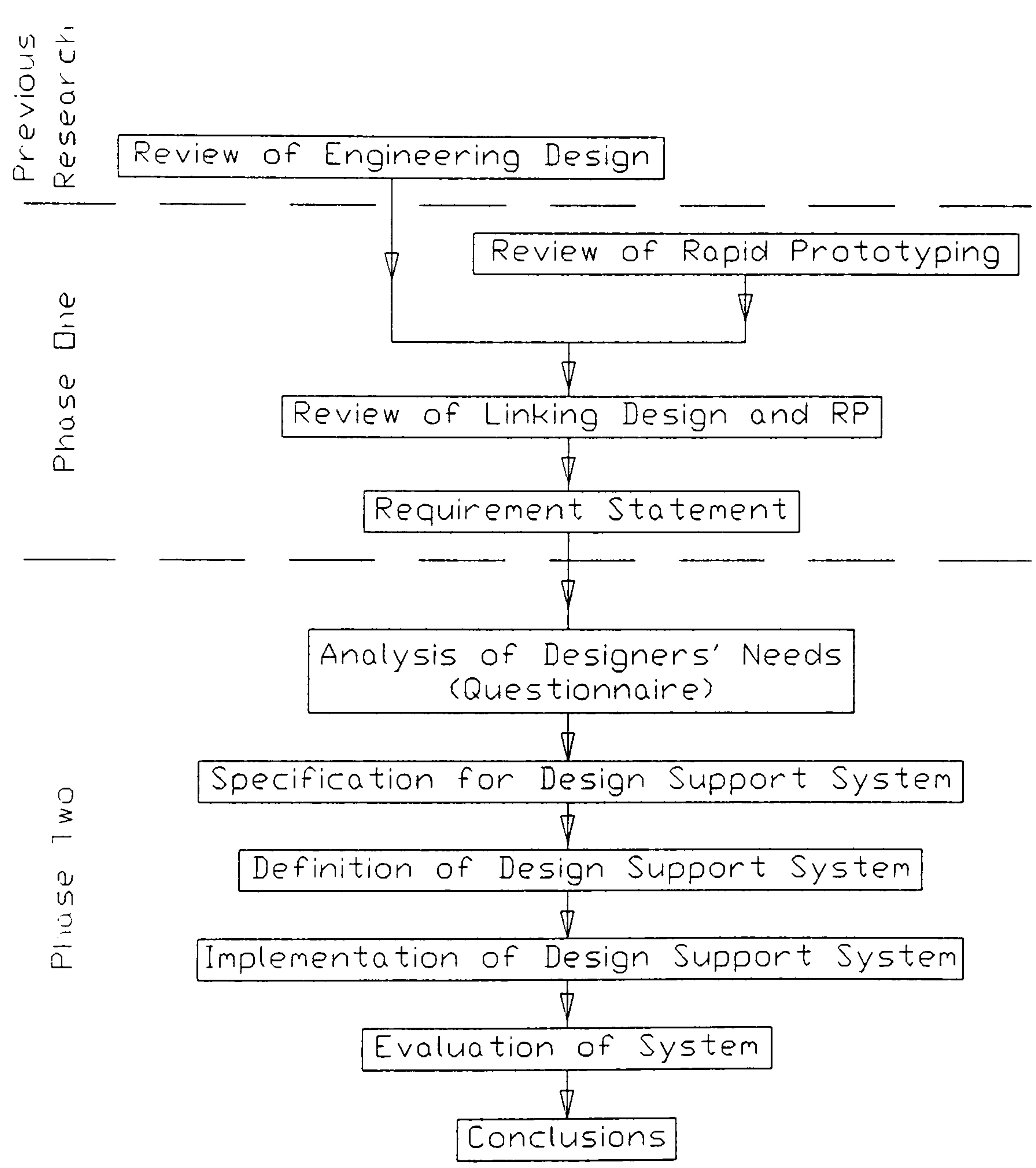


Figure 1.1 Two-phase research methodology followed during project.

The outcome of the first phase was a thorough understanding of the current state-of-the-art in terms of the relationship between design and rapid prototyping. It was discovered that although many links existed between design and RP, some of which were computerised links, few of these went beyond using simple geometric information to support RP. Therefore a requirement statement was developed which stated that a product model which contained all relevant data to link design and RP was needed to optimise the effectiveness of RP.

The second phase of the project was aimed at satisfying this requirement statement. This involved analysing the needs and aspirations of designers using RP through a questionnaire and then using this questionnaire to develop a specification for a design support system which would use the product modelling approach. This specification was then used to produce an implementation-independent definition of the system. Suitable hardware and software were then selected and a demonstration system was implemented and evaluated. Conclusions were then drawn from this evaluation showing that the use of a product model based computerised system did indeed provide the potential for optimising the effectiveness of RP. Finally, future work required to extend the system was identified.

Throughout the project, a series of Gantt charts were used to predict and monitor progress. Also, a strategy of continuous writing-up was used as much as possible.

1.3 Research Objectives

The following specific objectives were formulated during the initial phase of the research project:-

1.3.1 To determine what links are required between the engineering design process and rapid prototyping

1.3.2 To design a computerised system to support the designer's use of rapid prototyping

1.3.3 To implement the design support system and demonstrate the benefits its use will yield

1.3.4 To identify the future research and development which is required to transform the system into a commercial package

1.4 Structure of Thesis

As a result of the decision to research into the link between design and rapid prototyping, it was necessary to gain a thorough understanding of current RP technology, its role within the design process and what work had been done in the area of integrating it with engineering design. Therefore, the next three chapters of the thesis address the subjects of engineering design, rapid prototyping technology and the linking of design and RP. Chapter 4 ends with a requirement statement as to how RP must be better integrated into the design process using a feature-based product modelling system. Chapter 5 describes the development of a specification for such a system and the functionality of the system is defined in Chapter 6. The implementation of the system and its evaluation are the subjects of Chapter 7. Chapter 8 describes further work to be done and conclusions to the project are made in Chapter 9.

CHAPTER TWO

ENGINEERING DESIGN

2.1 Definition

The word "design" has many different meanings. Even when used in the context of engineering design there is still no universally accepted definition. Dixon and Simmons state that "design is the human activity of creating the concepts and the detailed instructions that specify the manufacture of material parts, products, and systems" [1]. Brown and Chandrasekaran define design as "a highly creative activity involving diverse problem-solving techniques and many kinds of knowledge" [2]. Sriram et al argue that "design can be viewed as the process of specifying a description of an artefact that satisfies constraints arising from a number of sources by using diverse sources of knowledge" [3]. For Liu and Trappey "the essence of design is that it is a plan to achieve a purpose or to satisfy a need" [4].

This author will not attempt to give yet another definition of engineering design but rather draw attention to some of the elements in the above quotations. The key words that should be extracted from these statements are:- concepts, detailed, manufacture, creative, problem-solving, knowledge, process, constraints and need. This section is aimed at giving the reader an understanding of what all these words mean when used in the engineering design context.

2.2 Classes of Engineering Design

One of the reasons it is so difficult to define engineering design is that it can be divided into several different classes. Each class of design is suited to a particular type of design problem. Sriram et al observe that design classes can be thought of as being bounded by the creative-routine spectrum which they divide into four regions: creative design, innovative design, redesign and routine [3]. Duhovik calls the four classes new design, innovative design, variation design and adaptation design [5]. Waldron only recognises creative, innovative and routine design, viewing redesign (or variation design) as a special case of routine design [6]. Brown and Chandrasekaran do likewise but simply use the terms class 1, class 2 and class 3 design [2]. These three classes are defined below.

2.2.1 Class 1 (Creative) Design

Neither the sources of knowledge required to solve the problem nor the problem-solving strategies to be employed are known. This type of design requires divergent thinking and will often result in totally new inventions. Very little design activity falls into this class and few designers are given the opportunity to undertake creative design. However, creative design is the most important part of the design process because it enables totally new solutions to be generated [7].

2.2.2 Class 2 (Innovative) Design

The sources of knowledge have been identified but the problem-solving strategies are still unknown. Existing knowledge will be applied in a new way to design new components or techniques. Some creativity is required for innovative design to be successful. This class of design is more common than class 1.

2.2.3 Class 3 (Routine) Design

A plan specifying the knowledge and problem-solving strategies to be used already exists. The designer is simply looking for a solution amongst a set of well understood alternatives. This class of design requires convergent thinking only and most design problems fall into this category.

2.3 Engineering Design Process

As might be expected, there is also debate about what the process of engineering design involves. At present there is not one generally agreed model of the design process [8]. The reason for this is that "models of design are subjective descriptions of the design process" [9]. Each person's view of the design process will depend on their own experience and opinions. However, the models of the design process proposed by Maher et al [10], Sriram et al [3], Ohsuga [11], Kinoglu and Riley [12], Brown and Chandrasekaran [13], Dixon et al [1] and Smithers [8] all agree that the activity can be divided into stages. The number of stages and their nomenclature is disputed but a "consensus" model shown in Figure 2.1 contains the stages that are generally agreed upon. These stages will shortly be discussed in detail. As the process progresses, an increasing proportion of the activity will be in the routine design class.

An aspect of the design process that is widely accepted is its iterative nature. Some stages or even the whole of the process may need to be repeated before an acceptable solution is found. Each time a stage is repeated the problem to be solved will be different and so the design is actually progressing towards the final solution. Colton and Dascanio describe this as an upward spiral rather than cyclic iterations on a plane [9]. Additional knowledge and experience are gained during the iterations. It is important to note that the design process both begins and ends with the customer.

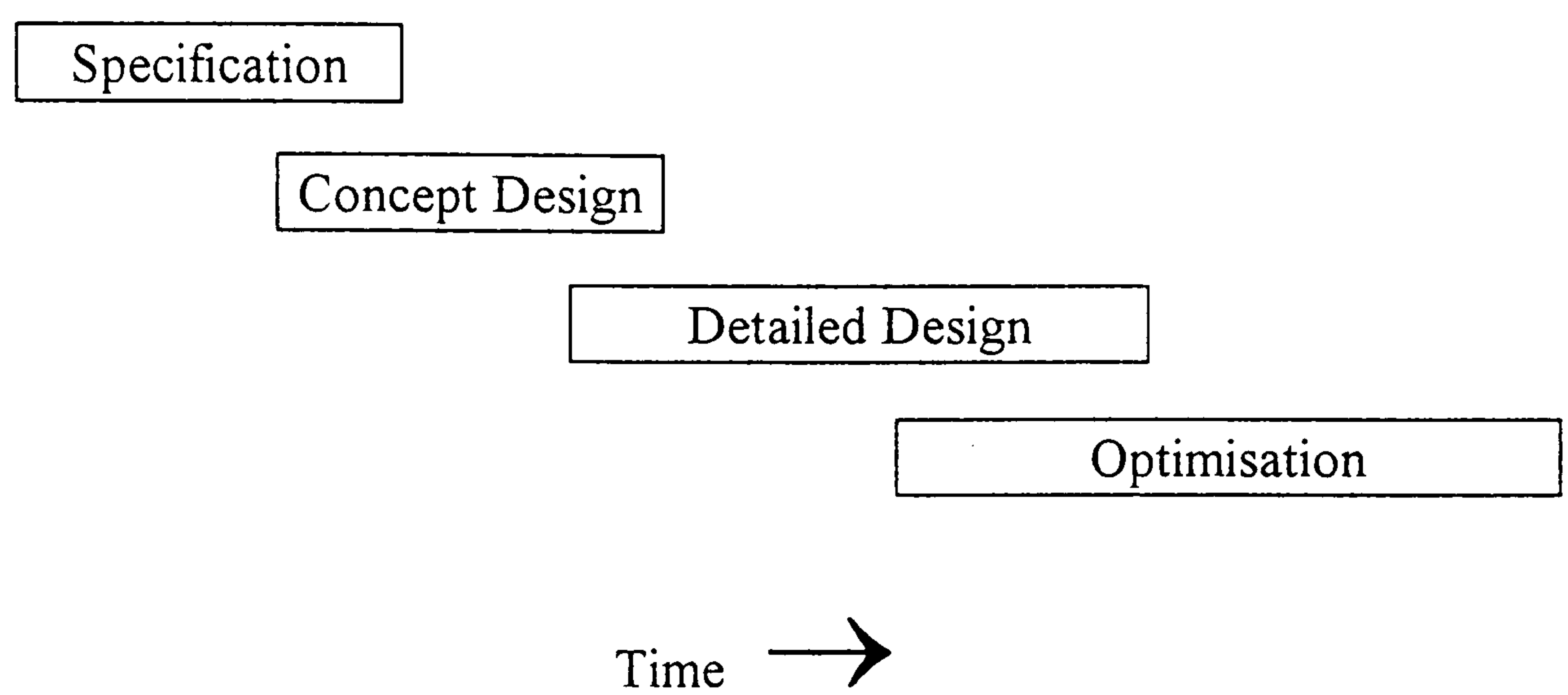


Figure 2.1 Stages in the engineering design process.

2.3.1 Specification Stage

Also called requirements description stage. The earliest stage in the design process involves translating customer needs or requirements into a formal specification. This should be a list of all the constraints that the designer must work within. It could contain detailed information on function, cost, aesthetics, size, weight, reliability, safety, durability, ergonomics, maintainability and anything else that will affect the customer's acceptance of the design. The specification should be part of a design brief that would also give the designer targets for the cost and timing of the design programme.

2.3.2 Concept Design Stage

Also called initial, rough or preliminary design stage. This stage involves generating ideas for designs that could possibly satisfy the design specification. Several alternatives may be generated in which case a selection procedure should be followed to determine which is most promising. This would normally involve evaluating each concept against key criteria from the design specification. Even if only one possible solution is generated it should still be evaluated. It may be that the outcome will be a decision not to proceed to the next stage of the design process. This is an important method of avoiding wasted design effort.

2.3.3 Detailed Design Stage

After a preliminary design has been selected, the next stage is to gradually add detail to the design until it is fully defined. This is often achieved using a top-down approach where a problem is decomposed into sub-problems and then into individual tasks. The objective is to arrive at a design that will fully meet all of the design specification and be as easy to manufacture as possible. This is where the bulk of the design effort will be concentrated. The output from this stage will be a complete "first-cut" of the design.

2.3.4 Optimisation Stage

Also called re-design stage. The detail design is evaluated against the specification which could possibly have changed. (Some design models treat evaluation as a separate stage in the design process.) Any deficiencies in the design are corrected and re-evaluated. This is where much of the previously mentioned iteration occurs. This part of the design process will include work that is often called development, i.e. the evolution of the design through simulation, testing of prototypes and manufacturing trials. The end result will be an optimised design that will be manufactured and distributed to the customer.

2.4 Use of Computers for Engineering Design

Computers have many roles to play in the engineering design process. They can be used for numerical analysis (such as finite element analysis), data storage, word-processing of engineering reports and other non-graphical applications. However, only one aspect of computers in engineering design will be covered here, that is computer aided design (CAD). CAD has been defined as "the use of a computer system to assist in the creation, modification, analysis or optimisation of a design" [14]. The characteristic of CAD that distinguishes it from other computer applications in design is its use of interactive graphics. Interactive graphics allow the product design to be created, viewed and modified by the designer using a visual display unit.

The development of CAD has gone through four major phases roughly coinciding with the past four decades [15]. During the 1950s interactive computer graphics were conceived but could not be implemented due to the poor performance of computers. In the 1960s interactive graphics became a reality with the development of the Sketchpad system [16]. Soon afterwards the term CAD was coined and by the end of the decade several commercial two-dimensional (2D) systems were available. The 1970s was the period that saw the introduction of three-dimensional (3D) modelling. This took CAD beyond the field of electronic draughting. Various organisations and standards were initiated to support the growing number of CAD users. Throughout the 1980s the most rapid development of CAD occurred. Surface and solid modelling were developed leading to a wide range of new application areas. Integration between CAD and computer aided manufacturing (CAM) became a reality. CAD systems moved from mainframes to workstations and micro-computers. The 1990s have seen increasing use of parametric modelling and a drive towards integrating CAD and CAM with non-engineering functions to achieve computer integrated manufacturing (CIM). Many of the terms used in this brief history of CAD are explained below.

2.4.1 Electronic Draughting

This term is synonymous with 2D CAD and emphasises the fact that when used to represent geometry according to 2D conventions such as BS 708, CAD is simply a substitute for a manual drawing board. The drawing is created in exactly the same way. Curves are used to create several views of the product and then annotation is added to relate the information required for manufacturing. Electronic draughting gives many advantages over manual draughting including improved clarity, less repetition of effort and a potential link into 2D CAM. However, they both suffer from the same fundamental weakness i.e. 3D shapes cannot be unambiguously represented by 2D drawings. This is why the emergence of 3D CAD was such an important development. For the first time the designer could "draw" in 3D.

2.4.2 Geometric Modelling

The heart of a CAD system is its ability to create a computerised model that represents the shape of the product being designed. This is known as geometric modelling [14]. Since most engineering products are 3D, it follows that CAD models also need to be 3D (only objects with constant thickness or rotational symmetry can be adequately represented using 2D drawings). Once the geometric model has been stored in the CAD system database, it is available for all manner of downstream activities. The three types of geometric modelling are described below.

2.4.3 Wireframe Modelling

Wireframe modelling is when the edges of the product being designed are represented by curves generated from mathematical equations. Typical curves used are straight lines, conics and splines generated from polynomial equations of varying degree. The advantage of wireframe modelling is the relatively low storage and processing capability demanded from the computer. Its disadvantage is that the design is not fully defined since there is no representation of the shape of the faces between the edges. This may be satisfactory for flat faces but is totally inadequate for complex shapes. By constructing several views of the 3d model, wireframe modelling can be used to generate detailed drawings. It can also support some types of finite element analysis (FEA) and numerical control (NC) part programming.

2.4.4 Surface Modelling

Surface modelling overcomes the drawback of wireframe modelling by providing a mathematical representation of the faces of an object. There are several different representation schemes available but most work on the principle of parameter transformation as shown in Figure 2.2. The values of two parameters (usually called u and v) are input to a set of polynomial equations to define the values of the x, y and z co-ordinates at that position on the surface. Some schemes use a single set of equations to define the whole surface while others use multiple sets, each set defining a “patch” on the surface. Surface modelling completely describes the shape of an object and can be used to support shell and plate elements in FEA, all types of NC part programming, rendered image generation and rapid prototyping.

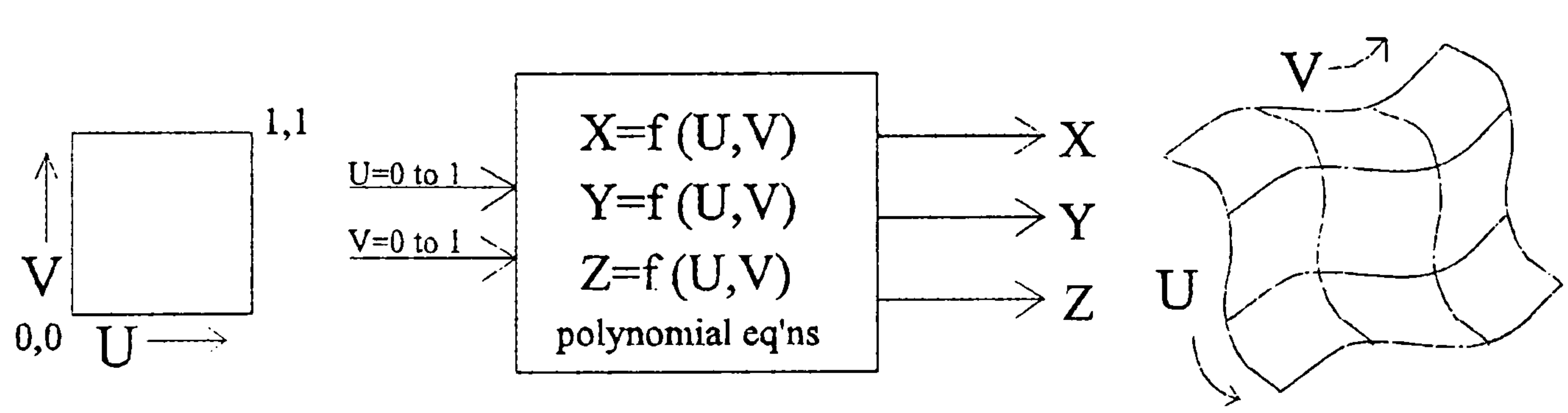


Figure 2.2 Parameter transformation in surface modelling.

2.4.5 Solid Modelling

Solid modelling effectively creates a fully defined surface model that is filled with solid material. For any point in 3D space, the system can ascertain if it lies within the object being designed, on its surface or outside the object [17]. This is the most complex form of geometric modelling and requires much greater computer capability both in terms of storage and processing. Solid modelling offers all of the benefits of surface modelling and some extra ones. It makes the designer's task easier by providing "building blocks" which can be combined to create the model. Typical building blocks are boxes, cylinders and spheres which can be combined using the boolean operations of union, subtraction and intersection. Volumetric attributes such as mass, centre of gravity and moments of inertia can be readily calculated. Preparation of detailed drawings is facilitated by automatic cross-hatching of sections and hidden line removal. Solid models can be used to drive automatic 3D meshing routines for FEA although the elements created are often tetrahedral and therefore of limited use. Finally, solid models are the preferred type of CAD model to support the use or rapid prototyping (RP). This is because the "watertight" nature of the model ensures an unambiguous definition of the RP transfer data.

2.5 Feature-based Design

In relation to engineering design, there is no agreement about the meaning and definition of the term "feature" [18]. One simple definition is "a bounded volume which may contain material or be void" [19]. However, the features of a component are often related to specific activities during the design and manufacturing process e.g. a hole is needed to accommodate a bolt, and may be created by a drilling operation. For this reason a more useful definition of a feature is "a geometric form or entity whose presence or dimensions are relevant to design and manufacturing functions" [20]. This definition also allows nonvolumetric features which are more useful for certain applications. Feature-based design (FBD) refers to the creation of a CAD model using a combination of these geometric forms. FBD differs from solid modelling in that non-graphical attributes such as surface finishes or tolerances can be attached to each feature.

A FBD package will provide a range of standard features such as holes, slots, bosses and grooves. It is possible to model quite complex components using standard features alone. However, there will be occasions when the standard range of features will not be sufficient. To overcome this problem, users must define their own features. One way of defining a feature is to construct a 2D profile and then sweep it along a vector. This technique could be used to create, for instance, a T-shaped slot. Another method is to modify a standard feature e.g. create a hole with a conical bottom. These user-defined features are stored in a library where they can be accessed for future designs. Using a combination of standard and user-defined features it is possible to create virtually any component shape.

A logical extension to FBD is to combine it with parametric modelling. This enables features to be described in terms of parameters rather than fixed attributes. Not only can the individual features be parameterised, but also their location with respect to the model. Some commercially available FBD packages already use this combination to provide extremely flexible modelling tools [21, 22].

The benefits of using FBD include the ability for the designer to create a model using natural shapes. These shapes can be selected according to the function of the component and its likely method of manufacture. When combined with parametric modelling, the advantages of easy modification and part families are added. A potential benefit is the integration of CAD and computer aided process planning (CAPP), eventually leading to the automation of the planning procedure [23]. The CAPP system would match each feature (with its manufacturing related attributes) to a particular manufacturing process. This would facilitate the technique known as feature-based machining.

2.6 Integration with Downstream Activities

Much mention has already been made of downstream activities. These are software applications which can use a CAD model as one of their inputs. Some of them, such as NC part programming and CAPP, are regarded as being CAM technologies. When CAD and CAM are linked, the term CADCAM is used. When other technologies, such as FEA, are also integrated, the term computer aided engineering (CAE) is often used. It is only when CAD is used as part of these wider activities that its full benefits can be realised. In general, the higher the level of data stored in the CAD model, the greater the potential for integration with downstream activities. Thus, feature-based design exhibits the most promising prospects.

The core of CADCAM integration is a common database. As the CAD data is created, it can be stored in a format that is accessible to other software applications. Some commercially available CADCAM systems use this method to provide totally integrated design and manufacturing software. A less desirable method is to use conversion routines to transform the CAD data into the formats used by other applications. This is a method very often used to achieve integration between software packages coming from more than one vendor. The possibility exists to integrate non-engineering applications using the same database. An example would be the provision of parts lists to aid inventory control. A common database used by all computer applications in an organisation is one of the aims of computer integrated manufacturing.

2.7 Conclusions

Due to its origins in electronic draughting, CAD has concentrated on assisting the detail design and optimisation stages of the design process. The designer is forced to think in terms of specific dimensions and configurations. As a result, conventional CAD systems do nothing to encourage creativity [24] and using CAD as an aid to concept design was, until quite recently, considered a dream [25]. Conventional CAD systems generate data of a geometric nature i.e. regarding the shape of the product. This makes them inherently limited in their ability to support the whole engineering design process [8]. Feature-based design goes a stage further by enabling function-related attributes to be attached to geometry. The ability to embed additional information in the CAD model has particular relevance to supporting manufacturing processes, including rapid prototyping.

CHAPTER THREE

RAPID PROTOTYPING TECHNOLOGY

3.1 Introduction to Rapid Prototyping

Rapid prototyping (RP) has been defined as "a process by which a solid physical model of a part is made directly from a three-dimensional (3D) CAD drawing" [26]. To take account of other sources of 3D data (such as medical imaging), the author believes that the term "CAD drawing" needs to be replaced with "electronic representation". This definition can be applied to a range of processes that provide an alternative to conventional manufacturing processes and tooling. The first RP system to become commercially available was stereolithography, first sold in 1988 [27]. Several commercial RP systems are now available, most of which use the methodology shown in Figure 3.1

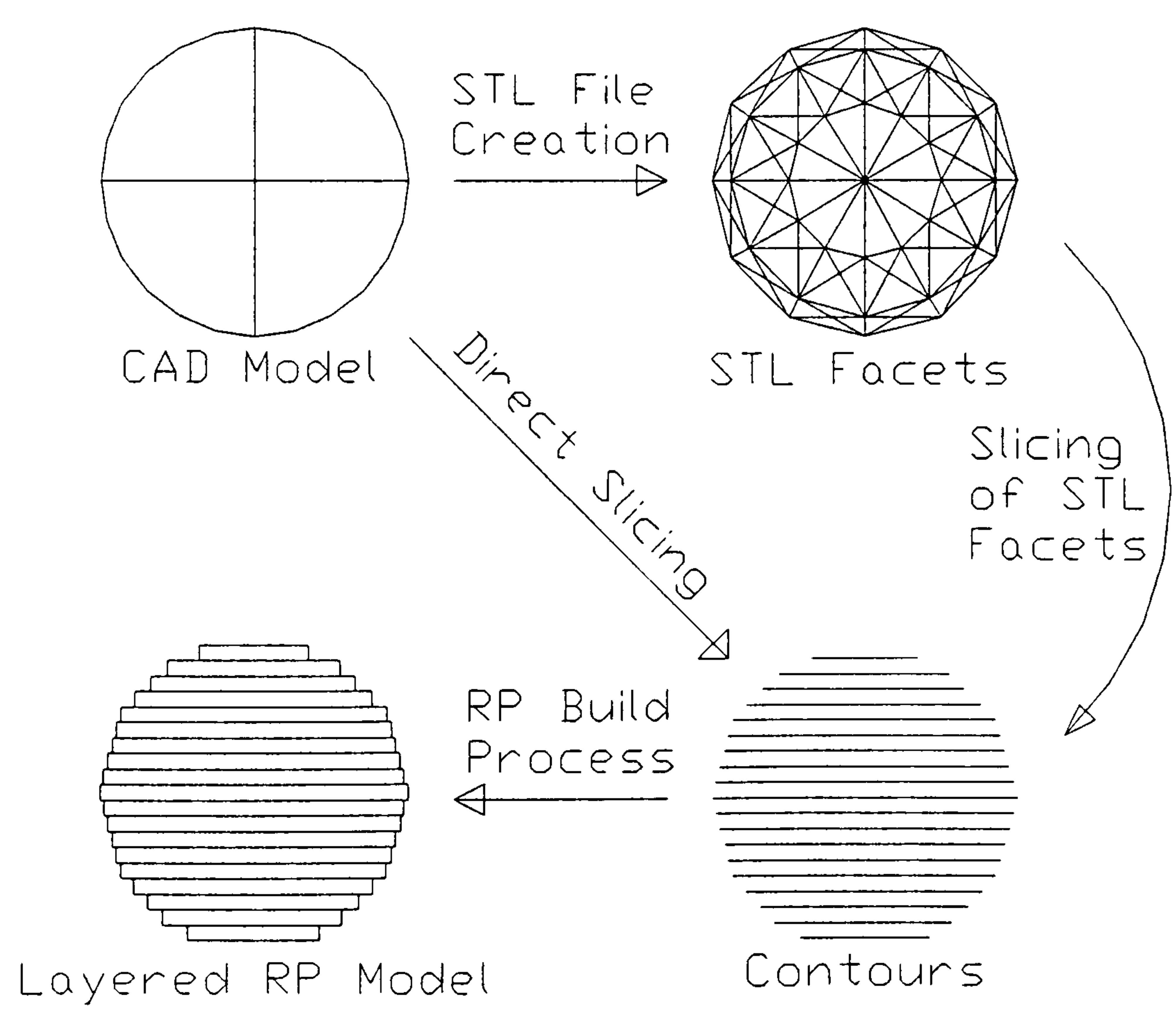


Figure 3.1 Methodology behind commercially available RP systems.

The geometry of a computer aided design (CAD) surface or, preferably, solid model is approximated using triangular facets and this faceted format is transferred to the RP machine computer where it is sliced into a series of two dimensional (2D) contours. These contours are used to drive a layer by layer fabrication process which constructs the 3D physical model. A slight variation to this methodology that is supported by some RP systems is for the CAD model to be sliced directly and the contours transferred to the RP system.

3.2 Leading Commercial RP Processes

The processes used in the five most common [28] commercial RP systems are described below, together with some of their strengths and weaknesses. A list of major strengths and weaknesses for each process is summarised in Table 3.1 [29].

Process	Strengths	Weaknesses
Stereolithography	Unattended Operation Good Accuracy Good Surface Finish	Requires Post-curing Limited Materials Requires Support Structures
Solid Ground Curing	No Post-curing Nested Components No Support Structures	Excess Material Waste Attended Operation Limited Materials
Selective Laser Sintering	No Post-curing Variety of Materials Limited Support Structures	Not Fully Dense Models Rough Surface Finish Some Support Structures
Laminated Object Manufacturing	No Post-curing No Support Structures No Warpage No Internal Stresses	Rough Surface Finish Delamination of Models Removal of Interior Excess Material
Fused Deposition Modeling	No Post-curing Variety of Materials Fast for Hollow Models	Requires Support Structures Seamed Surface Finish Slow for Solid Models

Table 3.1 Strengths and weaknesses of leading RP processes.

3.2.1 Stereolithography

Stereolithography was the name given to the first RP process to become commercially available. The original "Stereolithography" system was developed by a company called 3D Systems but the term is sometimes generically applied to other, similar systems. The process used by stereolithography is the solidification of a photoreactive polymer upon exposure to an ultra-violet (UV) laser beam (see Figure 3.2).

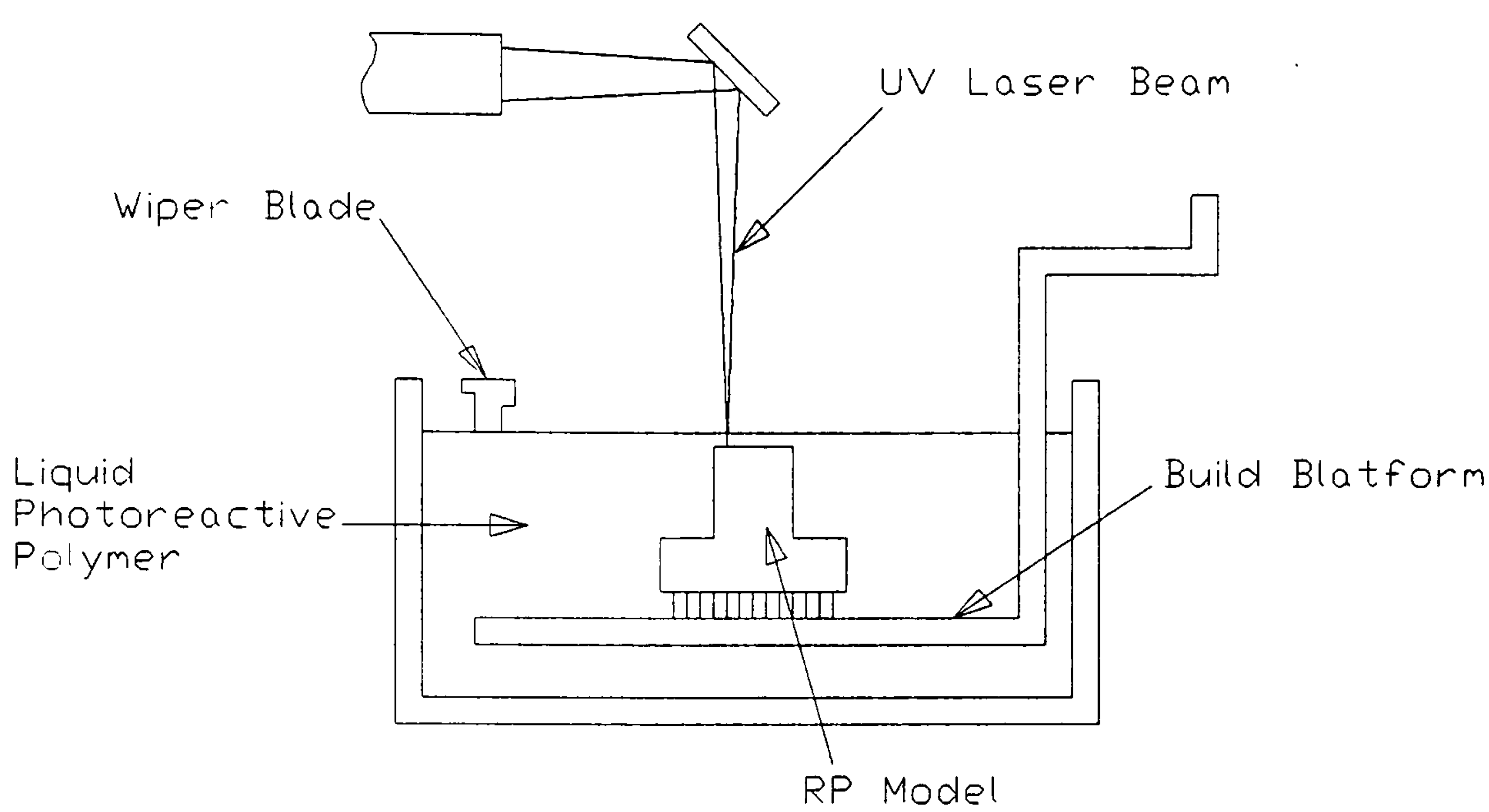


Figure 3.2 Principle of operation for Stereolithography.

The laser is directed by a pair of movable mirrors to scan across a vat of liquid polymer. The vat contains a build platform which is initially a set distance, *t*, below the surface of the liquid. The surface of the liquid in the scanned area is solidified and adheres to the build platform. The platform then descends, allowing the surrounding liquid resin to flow over the solid layer that has just been created. The platform then ascends to a height *t* mm lower than its original position and a wiper blade traverses across the vat to level the surface of the liquid. The laser once again scans to create a new solid layer which adheres to the previous one. This process continues until the whole model has been created as a series of layers, each one *t* mm thick. The platform is then raised completely out of the resin, the model is allowed to drain and then is ready for post-curing. This is where the model is saturated with UV light to solidify any remaining liquid polymer trapped in the model. This post-curing can be effected in the RP machine itself or the model can be removed to a separate curing oven.

Stereolithography models can be built from several different photoreactive resins with different material properties. The minimum layer thickness which can be achieved with 3D Systems' apparatus is 0.05 mm [30] and it is this parameter that largely determines the accuracy of models. If a model has overhanging geometry, support structures must be used. Generation of these can be achieved automatically but they can be difficult to remove and will worsen the surface finish of the model. The maximum build envelope for 3D Systems' stereolithography apparatus is currently 508 mm X 508 mm X 584 mm, although larger envelopes are available from other manufacturers [30]. The other vendors supplying stereolithography-type systems include:- CMET, Sony, Meiko and Tejin Seiki of Japan and EOS of Germany.

3.2.2 Solid Ground Curing

This process is similar to stereolithography in that it employs the solidification of photoreactive polymers by UV light. However, the polymer is solidified through instantaneous exposure to a UV lamp rather than a scanning laser (see Figure 3.3). The lamp is shone through a series of masks that are generated from the profile contours. After each lamp exposure, non-solidified resin is removed by a vacuum head and replaced with wax. The resin and wax are then cooled, machined flat and coated with a fresh layer of polymer. The process is repeated using a different mask for each layer until the model is completed. The finished model is surrounded by wax which can be removed by washing with hot water.

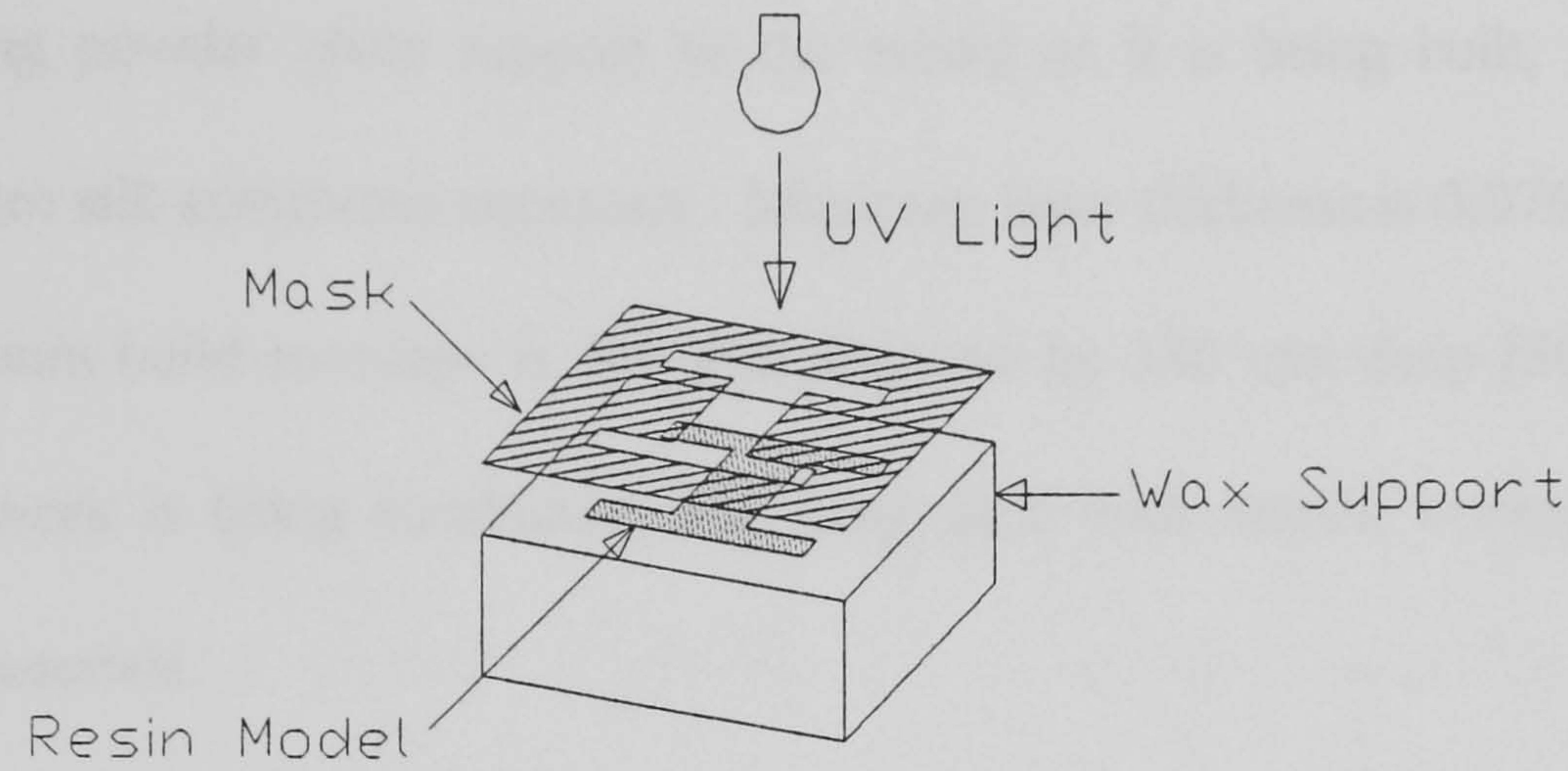


Figure 3.3 Principle of operation for Solid Ground Curing.

No additional supports are required with solid ground curing since the surrounding wax provides inherent support. It is possible to build several parts nested within one another such as an assembly. Minimum layer thickness is 0.06 mm and the maximum build envelope is approximately 500 mm X 350 mm X 500 mm [30]. Solid ground curing is a complex process with several operations and therefore requires a large and expensive machine. The process is sold by Cubital under the trade name of Solider.

3.2.3 Selective Laser Sintering (SLS)

This process uses a scanning CO^2 laser. The laser is used to selectively sinter a thin layer of powdered material (see Figure. 3.4). The powder can be wax or a thermoplastic material such as nylon or polycarbonate. A piston within the cylindrical build chamber which contains the powder is lowered, a fresh layer of powder applied using a roller, and the process repeated. Each layer is also fused to the one below. The completed model is surrounded by unsintered powder from which it must be removed. This is undertaken using a brush or compressed air. Chemical wiping of the part is also used to improve surface finish. Although the surrounding powder gives support to the model as it is being built, additional supports are still sometimes necessary. Minimum layer thickness is 0.076 mm and the maximum build envelope is 300 mm diameter by 380 mm deep [30]. Much research work is being conducted into using SLS with metals, composites and ceramic materials.

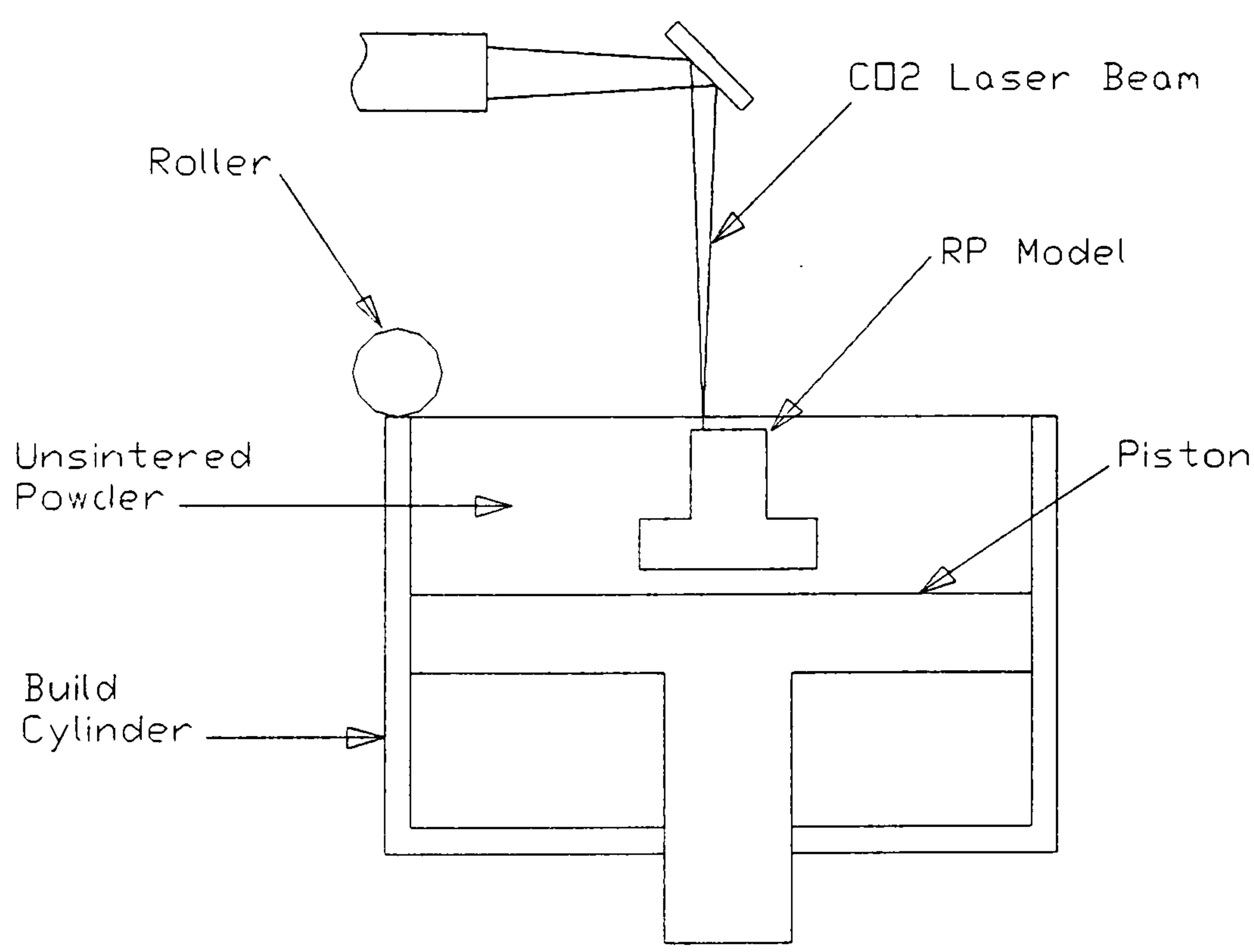


Figure 3.4 Principle of operation for Selective Laser Sintering.

SLS has been commercially available since 1990 and is sold by DTM of the USA. A similar system to SLS has been developed by EOS of Germany.

3.2.4 Laminated Object Manufacturing (LOM)

This process uses a CO^2 laser to cut profiles from sheet material (see Figure 3.5). The surrounding unwanted material is crosshatched by the laser. The sheet of material is then indexed by rollers and bonded to the previous layer. The process is then repeated. When the model is finished, it is removed by breaking away the surrounding crosshatched material. This can cause problems for enclosed volumes. The materials available are paper and polyester film. Models made from paper have a wooden appearance and are susceptible to moisture ingress if not treated with a waterproof coating. The surrounding material acts as an inherent support. The minimum layer thickness for LOM is 0.05 mm and the maximum build envelope is approximately 550 X 810 X 500 mm [30].

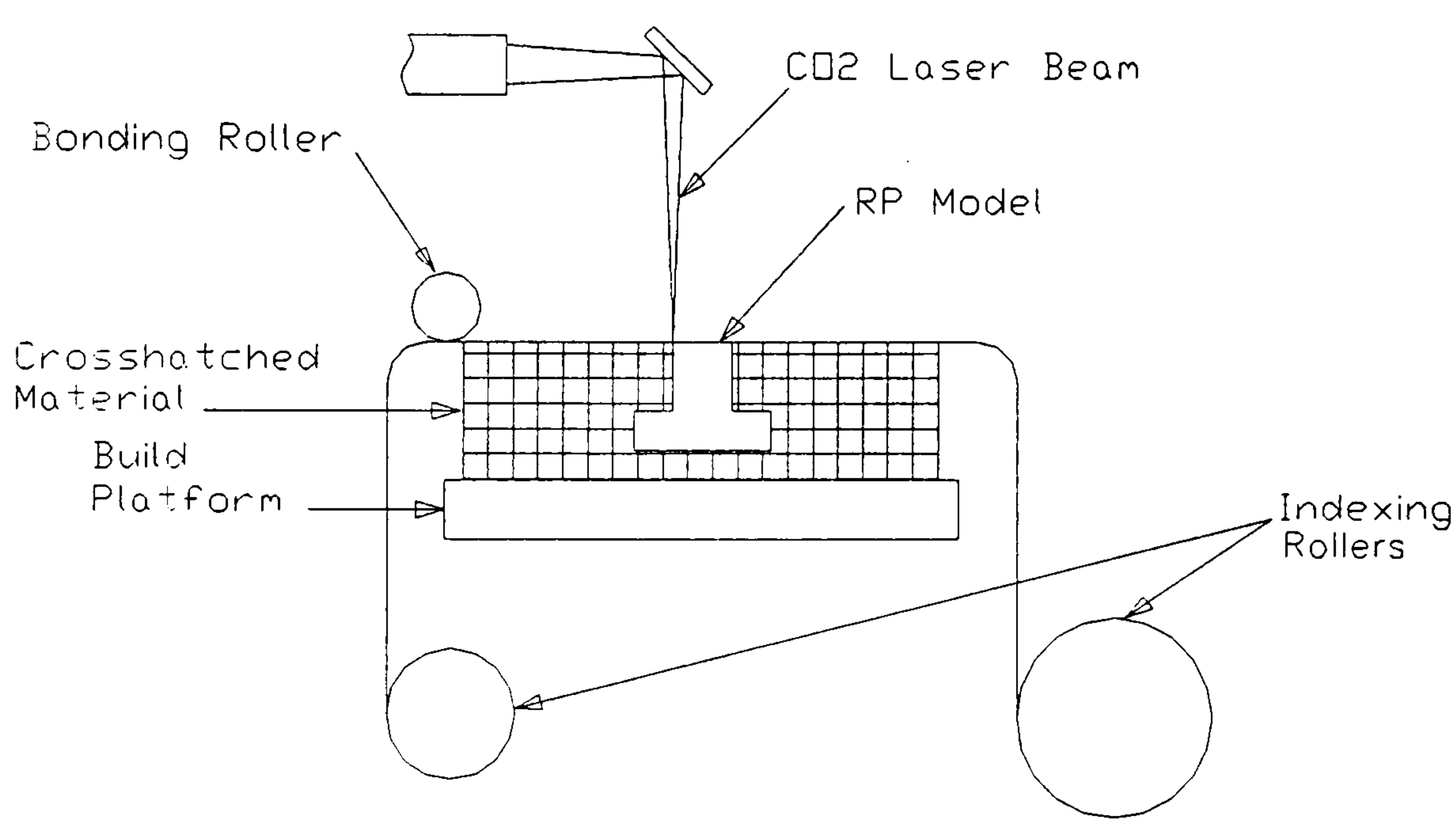


Figure 3.5 Principle of operation for Laminated Object Manufacturing.

LOM has been marketed by Helisys of the USA since 1992 and similar processes are sold by Kira of Japan, Kinergy-Hust of Singapore, Sparx of Sweden and Scale

Models Unlimited of the USA. The two latter processes require manual stacking of the layers.

3.2.5 Fused Deposition Modelling (FDM)

This process involves the extrusion of semi-molten thermoplastic material through a heated orifice onto a fixed base (see Figure 3.6). The extrusion head is moved in the X and Y directions while each layer is being deposited and in the Z direction between layers. The raw material (which can be wax or plastic) is supplied in the form of a filament. Extra supports are sometimes required and the process is more suited to hollow parts as solid parts are slow to build. Minimum layer thickness is 0.051 mm and the maximum build envelope is 254 mm cubed. The FDM system is marketed by Stratasys of the USA.

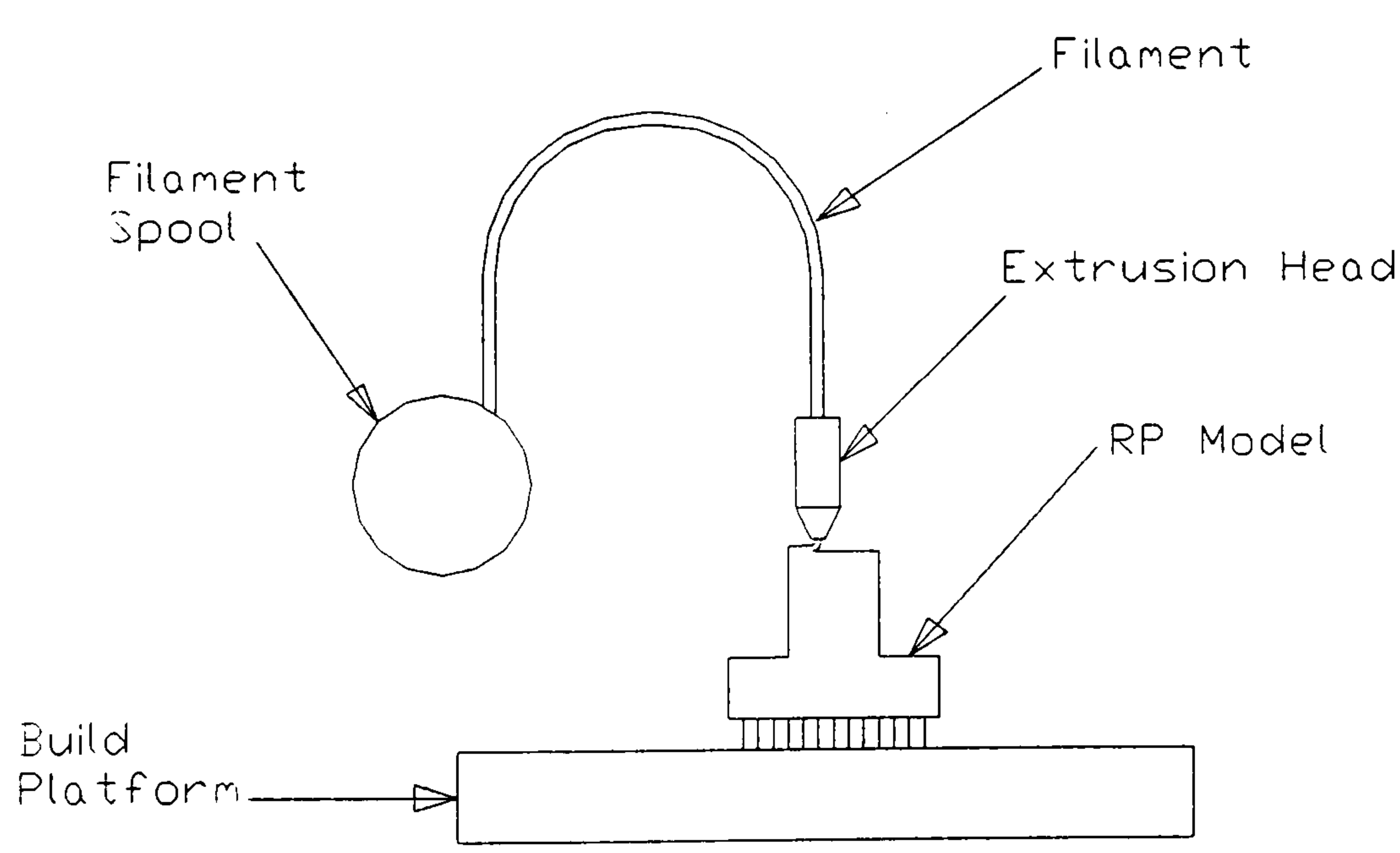


Figure 3.6 Principle of operation of Fused Deposition Modelling.

3D Systems have developed a raster-based extrusion process called Multi-jet Modeling (MJM). This has the advantage of the build-time being almost independent of the model geometry.

3.3 Other Rapid Prototyping Processes

There are many other RP processes besides those described above. Some of them are commercially available, but still not very widely used, whereas others are still at the research and development stage. A selection of those which are of particular interest are described below.

3.3.1 3D Printing

This process has been developed at the Massachusetts Institute of Technology (MIT) and works using the principle of selective bonding of powdered material. The process is quite similar to SLS except that the powder is bonded with a liquid binder rather than a sintering laser. A layer of powder is deposited and a plotting head (similar to that used for ink-jet printing) is used to apply the binder to the desired area. A new layer of powder is deposited and the process repeated. When the model is completed, it is removed from the unaffected powder and fired to cure the binder. A commercially available application of this technology is Direct Shell Production Casting which creates ceramic moulds for metal casting directly from a CAD model. Research is being conducted at MIT into producing parts with micro surface textures and micro internal structures using 3D printing [31, 32].

3.3.2 3D Plotting - Sanders Prototype

An American company called Sanders Prototype have developed an ink-jet RP system that uses two deposition heads, one for the build material and one for supports. The build material is a thermoplastic and the supports are made from wax. After one or more layers has been deposited, the model is machined flat to provide an even surface for continued building. Layer thickness is approximately

0.08 mm [30] When the build is completed, the wax supports must be removed by washing with kerosene.

3.3.3 Ballistic Particle Manufacture

This process deposits droplets of a molten build material through a small orifice using a piezoelectric pump. The deposition head is moved in 3, 4 or 5 axes and builds the model in a layerwise manner. The fact that the droplets can be deposited from a wide range of directions means that the need for supports is virtually eliminated. The process is marketed by BPM Technology of the USA.

3.3.4 3D Welding

This is a technique where a metal inert gas welder attached to a robotic arm is used to deposit steel or aluminium in a layerwise fashion. The robot is programmed to create the 3D shape that is required. The process uses a similar methodology to FDM but is aimed at producing metal prototypes directly. The work being conducted at Nottingham University has been able to produce models with similar accuracy and surface finish to sand castings [33]. When combined with a rotatable build platform, 3D welding can be used to construct models using several different build orientations. This reduces the need for additional supports.

3.3.5 Shape Deposition Manufacturing (SDM)

This technique, developed at Carnegie Mellon University, uses a combination weld-based deposition, computer numerical control (CNC) machining and shot-peening to create metal RP models. Besides the build material being deposited, a support material (also typically metal) is deposited around the model during construction.

CNC machining is used to create a smooth surface on the deposited material and shot-peening is used to relieve stresses. SDM avoids the stepped surface finish exhibited by most other RP processes [34].

3.3.6 Laser Generation

This involves directing a high-power laser onto the model being built and, simultaneously, feeding a cladding material into the laser spot on the surface of the part. The feed system can use material in the form of wire [35] or powder [36]. Although typically used in a layerwise manner, it would be possible to construct parts with a more complex build pattern.

3.4 Applications of RP Technology

The ability to create 3D physical models directly from electronic data can be used to support several activities within the engineering design and manufacturing process. It can also be used for non-engineering applications such as creating models from medical imaging data. However, only engineering applications are discussed here. Kochan states that RP models can be divided into three categories: design models, function models and manufacturing models [37]. Within each of these categories, there are several different applications of RP models (see Table 3.2). Each of these applications are described below.

Design Models	**Function Models**	**Manufacturing Models**
CAD Model Verification	Form and Fit Analysis	Plastic Moulding Patterns
Design Visualisation	Flow Analysis	Metal Casting Patterns
Proof of Concept	Stress Analysis	EDM Electrodes
Marketing Models	Mock-up Parts	
	Prototype Parts	

Table 3.2 Classification of the applications of RP models.

3.4.1 CAD Model Verification

It is not always possible to check that a CAD model is realisable just by looking at a computer screen. It is possible to construct CAD models that cannot exist in reality, especially when using surface modelling (see Figure 3.7). Even with solid modelling, some systems allow the user to create undesirable self-intersecting shapes like the one shown in Figure 3.7. Making a "hard-copy" using RP is one method of checking for these problems.

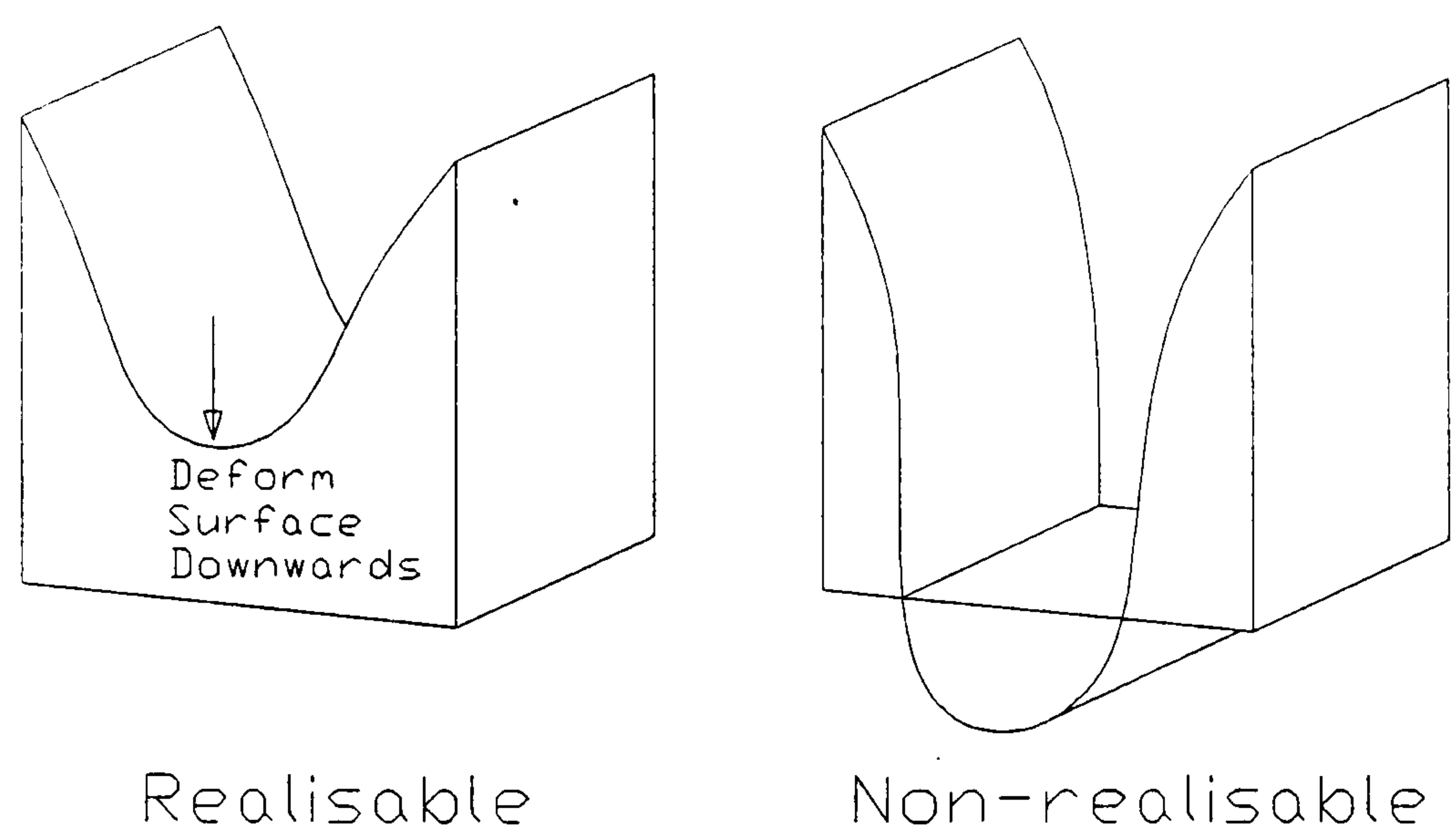


Figure 3.7 Example of a non-realisable CAD model.

3.4.2 Design Visualisation

In terms of being able to assess shape, size and ergonomic efficiency, there is nothing quite like holding an object in one's hand. This is where RP can offer designers a tool for their own use and as a means of communication to others. A physical model can be created quickly and presented to everyone involved in the product introduction process. Although virtual reality promises this sort of capability it is not likely to replace RP completely [38, 39].

3.4.3 Proof of Concept

This involves using an RP model to determine if a design concept is feasible at an early stage in the design process. This is advantageous because it prevents excessive expenditure on concepts that are doomed to fail. An example of this application is the creation of a coffee pot RP model which was used to assess the pouring characteristics of the design [40]. Obviously, a coffee pot design that cannot pour well is not worth developing further.

3.4.4 Marketing Models

This application really takes design visualisation a stage further by introducing the RP model to potential customers. It can be used to solicit their opinions at an early stage while there is still time to make desired changes. The RP model can be finished, e.g. by smoothing and painting, to take on the exact appearance of the final product. This is of particular value to products that have a high degree of aesthetic appeal. Some CAD systems can produce high quality, rendered images of products for use within marketing brochures. However, these are only 2D and do not allow the product to be handled.

3.4.5 Form and Fit Analysis

This is the simplest type of functional analysis that can be performed on a component. The RP model is used to check that the component is the correct shape to fit into its given envelope and to mate with adjacent parts. An example of this would be the assembly of a gearbox using RP models of the gears, shafts and housing. Once again, CAD systems can be used to perform assembly checks and clearance analysis but there is no substitute for the engineer being able to check that the gears actually mesh correctly.

3.4.6 Flow Analysis

Certain products have a requirement for aerodynamic or fluid dynamic testing. Examples are car bodies, engine manifolds, ship propellers, missiles and shower heads. It is possible to predict some performance values using computational fluid dynamics (CFD) but these packages are not 100% accurate. RP models that are very close to the shape of the finished product can be used for full-scale or scaled-down tests. These include wind tunnel experiments and cold-flow engine running. However, if the test environment is harsh, either through high temperatures or corrosive fluids, the RP model may have to be post-processed into a more suitable material. Post-processing of RP models is discussed later.

3.4.7 Stress Analysis

It is possible to use RP models for stress analysis despite the fact that they are seldom made in the final production material. The stress analysis results obtained from tests upon the RP model can be utilised for the final part by allowing for differences in material properties. The results obtained are by no means definitive, but they do allow for comparisons between several design variants [41]. This enables the part design to be optimised before the decision to manufacture real components is made.

3.4.8 Mock-up Parts

For some engineering applications it is of vital importance that a "mock-up" assembly of the evolving product be available for everyone on the design team to inspect and evaluate. Examples of this are automotive under-bonnet models and aerospace engine models. Normally such mock-ups would have to use model-makers' interpretations of designs or wait for a long time until prototype parts became available. With the advent of RP, it is now possible to have fast physical replications of the CAD model data, ready to assemble into the full-scale mock-up in a very short period of time. Problems exist where the mock-up is for a large product. RP machine build envelopes impose practical size limitations. One way to overcome this is for a scale model to be made. An alternative, used by Boeing for the 777 aircraft, is to replace the physical mock-up with the electronic CAD representation [42]. This will work with a new product that has been designed totally on CAD, but physical mock-up still has an important role to play in combining new components with older designs.

3.4.9 Prototype Parts

There is a growing number of "engineering materials" that can be produced directly on RP machines. Examples are ABS with the FDM system and nylon with SLS. Although, the material properties may not be identical to the final product, they are often close enough to be used for field trials and other functional tests. As the material capabilities of RP systems widens, it is likely that metal functional prototype parts will also be produced directly from CAD models.

3.4.10 Plastic Moulding Patterns

An RP model can be used as the master to create tools for plastic moulding. One method is to surround the model with liquid silicone rubber, allow the rubber to set, cut into the model to divide the rubber into two parts, remove the model and mate the two rubber moulds to create a cavity. Vacuum casting can then be used with polyurethane based materials to create a limited run of parts with similar characteristics to engineering plastics. A second technique is to use the RP model to create spray metal tooling. The part is mounted in a frame and thin layers of molten alloy are deposited until a shell of around 2mm has been created. This is then "backed-up" with a composite material into which cooling channels can be incorporated if necessary. The RP model is removed and the process repeated from the opposite direction to create the other half of the mould. When the two moulds are mated together, they can be used for limited run injection moulding. A further possibility is to use the RP models themselves as the injection mould tool, known as direct tooling.

3.4.11 Metal Casting Patterns

An RP model made of a suitable material such as wax or using a specialised build pattern such as 3D Systems' Quickcast™ can be used for investment casting. The model is dipped into a ceramic slurry several times until a shell is built up around it. The model is then melted or burned out leaving a cavity into which metal can be poured. Note that the RP model is sacrificed during this process. A major problem with this technique is the possibility of the shell cracking while the model is being burned out. Sand casting moulds can be created using RP models in exactly the same way as using conventional wooden patterns. The models are used as patterns which are placed in the sand and resin mixture. When the mixture has set, the patterns are removed and molten metal is poured into the resultant mould. Unlike investment casting, this process allows the RP model patterns to be re-used.

3.4.12 Electo-discharge Machining (EDM) Electrodes

EDM requires a conductive electrode that has the negative shape of the tool it is being used to create. RP could be used in three ways to provide such a tool. Either a conductive RP model is created directly, or a non-conductive RP model is coated with a conductive material, or the RP model is used as the master to form a conductive electrode. Current research work is aimed at producing a commercially viable technique to create EDM electrodes from RP models [43, 44].

3.5 Role of Rapid Prototyping within the Design Process

Relating the applications of RP listed above to the stages of design described in Chapter 2, it is obvious that RP can play a major part in the total design process. As soon as a complete geometric model of the design is available on a CAD system, it is possible to create RP models to perform many different functions. The role of RP within the concept, detail and optimisation stages of design is described below.

3.5.1 Use of RP within Concept Design

The main task of concept design is to generate and evaluate ideas. RP can help with evaluation of ideas by providing proof of concept and design visualisation models. The design or designs will not be complete, e.g. only exterior surfaces on a telephone. The computer model required for RP could be created using an engineering CAD package. Alternatively, a "styling" or industrial design system could be used [45]. A computer model created using such a system would not contain as much detail as a CAD model. There are also developments towards an interactive virtual reality system which can be used to create an electronic representation [46, 47]. Whatever route is used, as soon as the computer model has been completed, a physical prototype can be created for evaluation by everyone in the design team, including prospective customers. In this way, RP can help to engender a concurrent engineering approach right at the start of the design process.

3.5.2 Use of RP within Detailed Design

The aim of detailed design is to transform the selected concept into a complete "first-cut" design. This will typically involve many design engineers working in parallel on different aspects or components of the whole product. RP can help here by providing models for CAD verification and by creating a "mock-up" of the complete assembly. It is important to point out that RP could be misused in that designers could use it as a "safety-net" to catch errors that should have been detected on the CAD system. There is a fine balance to be stuck here between giving designers easy access to RP without making it so "cheap" that it will be used for a trial-and-error approach [48].

3.5.3 Use of RP within Design Optimisation

This part of the design process takes the first-cut detailed design, evaluates it against the design specification and, through a series of iterative loops, arrives at the optimum design which will then be manufactured. Much of this involves simulation, testing and analysis. RP has an extensive role to play both in the provision of models for various types of analysis and in the creation of prototype parts either directly or through the use of a secondary tooling process. The major benefit of using RP in design optimisation is that the time and money needed for individual iterations is greatly reduced. This means that more iterations are possible resulting in a better finished design [49].

3.6 Impact of Rapid Prototyping upon the Designer

The range of uses to which RP can be put indicates that it is a key technology that should be taken into consideration throughout the design process. However, this is only part of the argument for integrating RP into the design process. As RP capabilities increase, it will offer more possibilities for the designer. It is no longer just a quick way of making models, but rather a new set of manufacturing processes that can be used either directly or indirectly (through secondary processes) to produce finished parts. The future impact that RP will have upon the possibilities available to a designer are described below [50].

3.6.1 Increase in Part Complexity

The fact that RP is a freeform process means that complexity of shape is not a limiting factor. Therefore, more complex parts which perform several functions can be created without any significant increase in lead time or cost. This will lead to a reduction in the number of parts required in an assembly with a subsequent decrease in design and manufacturing costs.

3.6.2 Reduction in Material/Weight

RP enables strength to weight ratios to be optimised using variable internal structures, large thin walls to be created and parts to be made without the requirement for wasteful machining from stock.

3.6.3 Reduced need for Design for Manufacture

Parts can be designed without the need for draft angles, parting lines, fixture location holes and other constraints imposed by particular manufacturing processes. This will reduce design effort and the need for time-consuming discussions about manufacturability requirements.

3.6.4 Increase in Customer Acceptance

Parts can be designed to meet customer demands that would otherwise be impractical due to manufacturing considerations. For example, sculptured surfaces which are aesthetically pleasing are entirely feasible.

3.7 Future Potential of RP

RP has yielded many benefits including quicker model making, improved design visualisation and evaluation, less expensive prototype tooling and an overall reduction in the length of the design and manufacturing process. As a result, it has been readily adopted by many manufacturers leading to an impressive rate of growth in worldwide RP machine sales (see Figure 3.8.) [51]. This has been matched by an ever increasing number of research articles on RP appearing in a wide range of journals and conference proceedings. With so much activity in the field, it is not surprising that new RP systems and applications are constantly being developed.

In future years, RP machines will become faster, more accurate, easier to use and less expensive [39]. This should also lead to them becoming more commonly used. Already they are competing with many conventional manufacturing techniques for prototype and tooling production. It is also likely that they will soon be used for small batch production [52]. Consequently, RP should receive the same consideration during the design process as more traditional manufacturing techniques. Furthermore, RP is already changing the way the design process is executed. As the flexibility of RP techniques increase and designers learn how to more fully exploit this, the nature of designs themselves will change. Therefore, RP must not be treated simply as a useful "bolt-on extra" but rather as an inherent part of the design process. Only then can it be used to its maximum effectiveness.

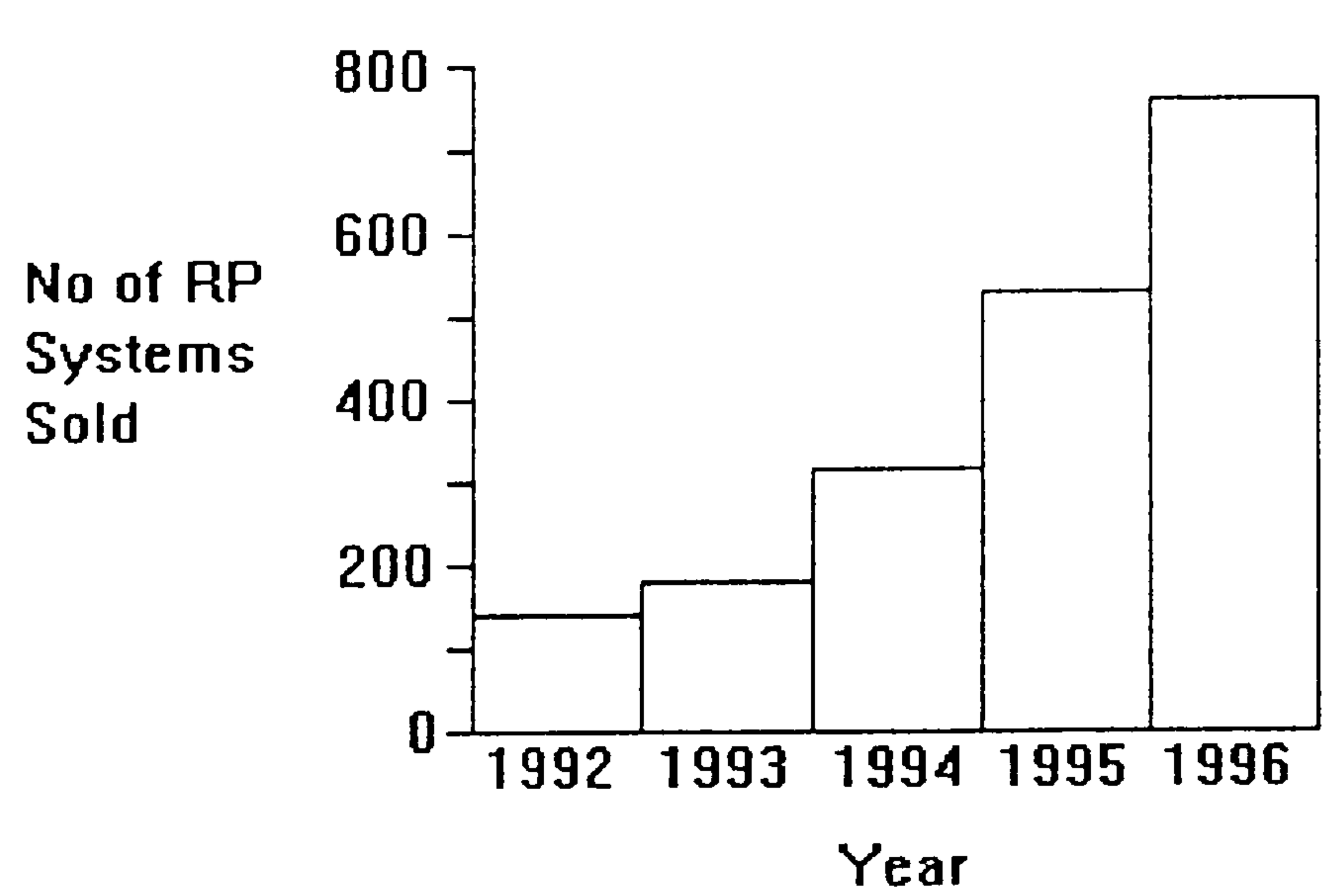


Figure 3.8 Growth of RP sales.

3.8 Conclusions

The field of rapid prototyping technology is growing in several ways. More people are using it, the processes and materials available are increasing and the range of applications it can be used for are widening. It is to be expected then, that its impact upon engineering design will also grow. It is essential that the link between design and RP is fully understood and that any weaknesses in this link are identified. This is the subject of the next chapter.

CHAPTER FOUR

LINKING DESIGN AND RAPID PROTOTYPING

The current link between design and rapid prototyping has two elements. The first is the procedure or methodology followed by the designer who is considering the use of RP. The detailed procedure followed when considering the use of RP will vary from company to company and even from one designer to another. However, this author has identified four key steps which should be part of any procedure aimed at ensuring the effective use of RP by designers. These steps are described in the first section of this chapter. Failure to follow any one of these steps will result in a weakened link between design and RP.

The second element of the link between design and RP is the computer software used to support the procedure followed by the designer (or at least some parts of it). The aim of such software is to assist the designer in the decisions and processes which must be undertaken before RP can be used. A review of the software which is currently available or being developed is given in the second section of this chapter. It will be seen that although a large amount of software has been developed, there are inadequacies in both the integration of software tools and the range of data which they use. This leads to a second source of weaknesses in the link between design and RP.

Having identified the weaknesses in the link between design and RP, this chapter ends with a "requirement statement" which first of all highlights the need for better integration between design and RP and then goes on to state what is required to address this need.

4.1 Ensuring the Effective Use of Rapid Prototyping

RP has an important role to play in shortening lead-time, reducing costs and improving quality. However, RP may not always bring improvements to the design process. It must be used effectively. Therefore, whenever the use of RP is being contemplated, there are four key steps which must be followed by the designer and/or other support personnel. Each step is a pre-requisite for the next to be performed. The end result will be a model, created using the appropriate RP technique with the optimum build parameters, which fully satisfies the designer's requirements. These steps are discussed below.

4.1.1 Determining if RP is Appropriate

It would be foolish to assume that RP is always the most appropriate way to produce a physical model. Indeed, even the necessity of building a physical model must be questioned. The advent of photorealistic CAD rendered images and immersive virtual reality systems has encroached on some of the traditional roles for physical models [38]. However, assuming that the need to build a model has been established as genuine, RP must be evaluated against its rivals which include manual model-making and CNC machining.

RP has both strengths and weaknesses. On the positive side, it is totally freeform, requires no tooling or fixtures and can make almost direct use of CAD data. However, its range of materials is limited, its use of layers gives rise to a "stair-stepping" effect (see Figure 4.1) and it is relatively expensive. Therefore, before its use can be justified, it is necessary to draw a comparison between RP and the available alternatives. This must be done on a part-by-part basis as the balance between the pros and cons will be different in each case.

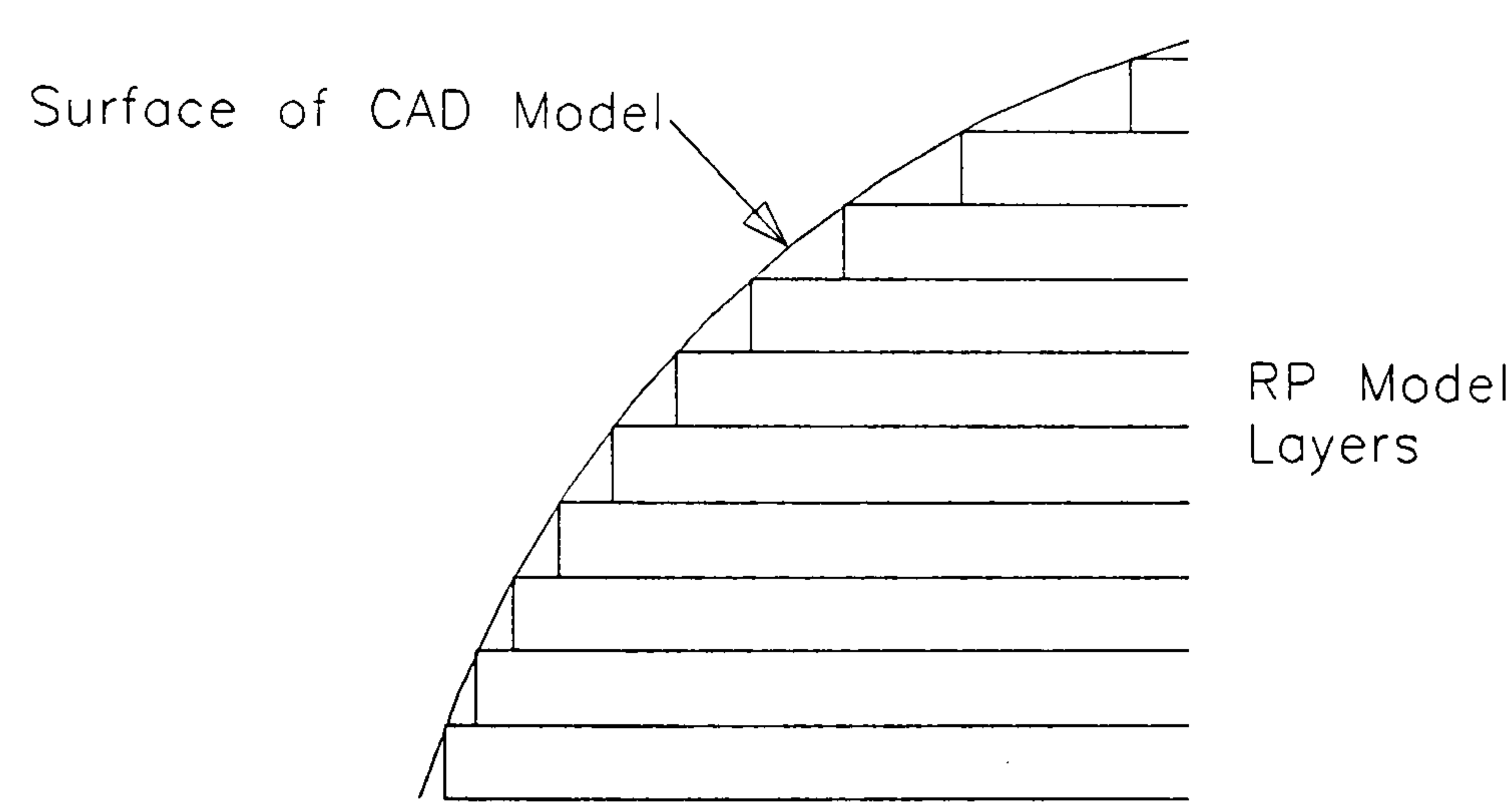


Figure 4.1 Stair-stepping effect caused by use of layers.

Kochan has developed a methodology for comparison which uses cost and time as its main criteria [50]. For both RP and CNC milling, cost models have been produced which take into account the various tasks involved in each technology. These cost models require input about the geometry of the specific part in question, and assume that the CAD model is already available. Ideally, the decision on whether or not to use RP should be taken before the CAD model has been created. This is because the use of RP may impose some restrictions on the model (most notably the requirement for surface or solid modelling) or alternatively it may create new possibilities e.g. the creation of several alternative CAD models to undergo concurrent prototype evaluation. This presents a quandary as it is difficult to produce reliable time and cost estimates until after a CAD model has been produced. However, it is possible to estimate whether build time and cost would be less for RP than CNC simply by asking some pertinent questions about the component being designed, e.g. how complex is the design, what size is the component, what material must the model be made from.

The decision to use RP or some other model-making process should be jointly taken by the designer, who knows the model's requirements, and support personnel, who know the capabilities of RP and the other processes. If RP is being operated as a "stand-alone" technology, it may be difficult to find support personnel with this knowledge. However, if it is being used in a model shop that also has access to manual and CNC facilities, this should not be a problem. The requirement for a joint decision could also be hindered if an "over-the-wall" relationship exists between the design and RP functions. This is more likely if an outside bureau is being used but could also exist with an in-house facility.

The objective of this first step is for the designer to ascertain if RP should be used. Assuming that its use has been justified, the CAD model can now be created or modified taking RP into consideration. Once this has been completed, the next step is to select the most suitable RP technique.

4.1.2 RP System Selection

The range of commercial RP systems available is always expanding. This means that a choice has to be made as to which RP technique to use. For some organisations this will be a one-off decision concerning which machine they should buy. Several one-time-purchase system selection methodologies have been suggested. Most of these methodologies work on the principle of following several steps. In the methodology developed by Kepner and Tregoe, [53] the first step is to list the organisation's absolute requirements. Then, a list of system capabilities that would be desirable but not essential is generated and importance factors assigned to each item. Each system that offers all of the absolute requirements is then assessed on a scale of 1 to 10 against the desired capabilities. The rating is multiplied by the weighting for each item and the products summed. The optimum system will be the one with the highest overall score.

The methodology described by Burns [54] begins with a decision on whether or not to buy an RP system. This is achieved by comparing the costs of running a system against the benefits that have been identified. The next step is to follow a benchmarking process similar to that of Kochan (see below). The final stage is to assess the RP system vendors in terms of the support they offer.

The 1993 OSTEM Rapid Prototyping report [55] recommends a range of RP systems to be considered for different applications. For example, companies who make a large number of sand castings should consider LOM, SLA and Solider.

The problem with this kind of prescriptive approach is that it soon becomes outdated as new technologies become available.

For Kochan, [37] the selection methodology takes the form of benchmarks chosen from one of three categories:-

1. A single benchmark part that is representative of all a companies products.
2. Several benchmark parts that represent the part families produced by a company.
3. A "challenge-testparts" benchmark where complex parts are designed with the express purpose of testing the capabilities of RP systems.

The benchmark approach has also been followed by Chrysler [56] who undertook a detailed cost comparison of several systems for a small automotive part. Challenge-part benchmarks have been developed by the SLA User Group [57], Lart [58], Juster and Childs [59], Iuliano et al [60], Jayaram et al [61] and as part of the Intelligent Manufacturing Systems Test Case on Rapid Product Development [62]. The weakness with all such benchmarks is that they are restricted to the characteristics of one part and different benchmarks will give different results.

A problem common to all the above methodologies is that they are aimed at making a once-and-for-all decision. They do not facilitate the selection of an RP system on a part-by-part basis. This capability is becoming increasingly desirable as large companies and RP service bureaux have made deliberate decisions to purchase several systems to increase their flexibility. Therefore, they have to choose between these systems for each part they build.

Some work has been done in the area of RP system selection for individual parts. Optimat have developed an RP feasibility assessment model [63] which gives consideration to individual part characteristics. This model consists of a table which lists RP systems against part parameters relating to function, size and geometric features. For each part parameter, the RP systems are rated as having distinct feasibility or limited feasibility. Another attribute of this model is that it compares RP technologies against CNC and sheet metal forming. In this way it is also acting as a decision aid on whether to use RP or a conventional process. The combining of the decision about using RP with the choice of RP system seems to be logical. However, one problem with this strategy is that the cost and timing data required to compare RP processes needs to be very accurate and will not be calculable until a CAD model has been created. Ideally, the decision on whether or not to use RP will be made before the creation of a CAD model.

Once again, the choice of RP process should be a joint decision between the designer and RP support personnel. The outcome of this step will be a decision to use a particular RP system to build a particular model. The next step is to prepare for the transfer of the model data from CAD to the RP system.

4.1.3 Data Exchange for RP

There are several different ways of representing geometry within a CAD system, e.g. Bezier surfaces, B-spline surfaces, B-rep solids and CSG solids [64]. Also, each different CAD system uses its own proprietary data format. As a result, it is desirable to have some sort of common or neutral format to transfer data to RP systems. One such format has become dominant within the RP community and is known as STL [65]. This format allows for the surface of an object to be approximated by a series of triangular facets. It is a simple but rather inefficient method as there is duplication of data for the co-ordinates representing the corners of each triangle. A thorough treatment of the strengths and weaknesses of the STL format is given by Jamieson and Hacker [66].

STL is by no means the only available format for transferring data from CAD to RP. Other faceted formats are available [67, 68] and there is also the possibility of using a general purpose CAD exchange format such as IGES or VDA. In all of these cases, the aim is to pass a complete representation of the component geometry from CAD to RP.

A second, radically different approach is to make use of the fact that all commercial RP systems are currently based on layered manufacture. This means that at some stage the 3D representation has to be converted into 2D contours via slicing. With STL, this is done after the data has been transferred from the CAD system. However, there is an alternative strategy that involves creating the slices within the CAD model and transferring these to the RP system as a series of contours. This is often referred to as direct slicing and RP exchange formats have been developed to support this methodology [69, 70]. It is a much more efficient method of transferring data as only the geometry that is actually required is passed to the RP system. However, it dictates the direction of build for the RP process which can be disadvantageous (see section 4.4) and it causes some difficulty with support generation.

In terms of transferring CAD geometry, the designer must choose between the different alternatives available. The choice will very often be determined by what formats are supported by the CAD system and the target RP system. An exchange file is then generated and transferred to the RP system via a direct link, e.g. the Internet, or through a "hard" medium such as a 3.5 inch diskette. In theory, the RP model can now be built using the appropriate build parameters. However, exchange files must always be validated and sometimes require a degree of repair work. A more fundamental problem is that the exchange of geometry alone does not give the RP operator all the required information to determine optimum build parameters. The exchange file should be accompanied by a drawing or textual document that defines other attributes of the part such as the material to be used, required tolerances, shrinkage factors, surface finish, etc. Even then, dialogue between the designer and the RP operator will be necessary to ensure continuity of design intent. This should prevent the "over-the-wall" attitude to RP that is sometimes displayed by designers.

4.1.4 Selection of RP Process Parameters

This step of RP implementation is normally undertaken solely by the system operator who is totally familiar with machine capabilities. It has been likened to the process planning function for conventional manufacturing operations [71]. However, Kruth states that there is not the same requirement for defining operation sequences as the part is produced in one operation [72]. This would be true if the model itself was the end result. However, when one or more secondary processes are used, operation planning does come into play [73]. Starting with the STL (or other exchange file format) representation of the CAD model, the optimum process parameters for the chosen RP system must be selected. Some of these parameters will be specific to individual RP systems, e.g. for stereolithography there is build style (ACES or Quickcast™), laser cure depth, z-wait during recoating. Others are common to most RP systems and include choice of material, build orientation, layer thickness and critically, choice of secondary processing.

The selection of process parameters can have a profound effect on the quality of the RP model. The material properties, model accuracy, surface finish and dimensional stability will all depend on the parameters chosen. Therefore, although they will be chosen by the RP operator, it is essential that the designer has conveyed fully the model requirements that will be used to select the parameters. Also, the choice of parameters will partly determine the cost and build time for the RP model. For example, build time largely depends on the maximum vertical dimension of the model. This in turn will be determined by the build orientation.

For these reasons relating to quality, cost and timing, it is essential that the optimum process parameters are selected for each RP model that is built. When left to the judgement of the RP operator, the quality of the decisions made will depend heavily upon individual knowledge and past experience. This is satisfactory as long as there is an adequate supply of personnel with these attributes. However, as the RP market continues to expand and the variety of systems grows, it will become more difficult to find operators with all the necessary skills.

4.1.5 Using Rapid Prototyping at Different Stages of the Design Process

The four steps described above should be followed every time a model is required during the design process. Several models may be needed at different stages of the design process, each with its own requirements. During the concept design stage, model accuracy and material are not important issues as the requirement is for proof of concept and visualisation models. Detail design requires models for CAD verification and "mock-ups", hence accuracy now becomes essential whereas choice of material is still flexible. For design optimisation models, both accuracy and material selection are crucial as the models will be used for analysis and secondary processes where particular material properties will be required. Therefore, it is likely that different RP techniques and build parameters will be selected for different types of models. The complexity of this procedure and the number of decisions that must be made have lead to the development of many software tools to support RP. These are discussed in the next section.

4.2 Software Tools for Rapid Prototyping

The fact that RP is a computer-based technology makes it especially suited to application-enhancing software tools. Many such tools have been developed through research programmes and some are commercially available. These can be categorised into several areas, each one dealing with a particular problem in the application of RP. These areas are discussed below.

4.2.1 System Selection

Although several selection methodologies have been suggested, only a few software tools to aid in this process have been identified. As part of a computer aided process planning (CAPP) package for RP, Muller et al have developed a database of system capabilities which can be evaluated against part definitions [73]. Additionally, the database contains information on NC milling and consequently is also acting as a decision aid on whether or not to use RP. The database approach to system selection has also been used by Phillipson and Henderson [74]. In this system, a series of algorithms are used to predict the build time and cost for several RP techniques. Narayanan et al [75] have developed a rule-based expert system which acts as an RP advisor. The user is asked a series of questions and the inference mechanism of the system uses the answers to recommend which technique to use or buy.

4.2.2 STL File Manipulation

The problems associated with the use of the STL format have long been recognised [76]. As a result software tools are required to help overcome these problems. One such tool is the standard software package which is supplied by 3D Systems as part of their Stereolithography system. This package enables the RP operator to view the STL file, scale it and reposition and reorient it. It also checks for any errors in the file e.g. missing facets, and will attempt to repair any such errors so that slicing of the file can commence. This package is rather limited in its capabilities and so other tools have been developed to provide improved functionality [77, 78, 79, 80]. These software tools enable STL files to be split, merged, shaded, converted to other formats, etc. A particularly imaginative example of software for STL file checking is the use of virtual reality to move the user around inside the STL file [81]. Software has been developed at Colorado State University which will import STL files and then allow the user to "sculpt" the resulting mesh of triangles [82]. It is clear that the functionality of STL manipulation software is advancing rapidly.

Some RP systems require support structures to be generated before a model can be built. Once again, 3D Systems supply this facility in their software package through a choice of two third-party modules called "Bridgeworks" [83] and "MAGICS" [84]. These modules will automatically create the required supports for a given STL file. Sometimes, more supports than absolutely necessary are created and manual editing can be used to reduce these. Other software tools for the generation of supports have been developed by the Stevens Institute of Technology [85], and POGO International [86]. The POGO software also includes STL editing capabilities.

Once an STL file (or files) has been checked and any necessary supports generated, the next stage for the computer software is to slice the file. Again, there is standard software available for this from the RP system vendors but alternative tools have been developed by others. Clemson University's CIDES software [87, 88] allows STL files to be viewed and modified, supports to be generated and slicing to be undertaken. A similar workbench of tools has been developed by DeskArtes under the name of Rapid Tools [89]. In addition this software can also create STL files from neutral CAD formats such as IGES, perform boolean operations on STL files and create offsets from STL files.

4.2.3 Direct Slicing

The principle behind all of the tools in Section 5.2 is that because STL has become the current "de facto" standard for RP, the industry's requirement is for better ways of handling these files. An alternative viewpoint is that direct slicing of the original CAD data offers major benefits over using STL and that software tools should be provided to support this strategy. The benefits of slicing a CAD model directly are listed by Jamieson and Hacker [66]:-

1. Reduced file size
2. Greater accuracy (no approximation with facets)
3. Reduced RP machine processing time (no slicing)
4. Elimination of repair routines (assuming correct contours)

Several software tools have been created to provide the capability of direct slicing [66, 90, 91, 92, 93]. In each case, the software also incorporates the facility of adaptive (or variable) slicing. This enables the spacing between slices to be tailored for the changing geometry of the part. Where the geometry is fairly constant, large spacing is used, where it is changing rapidly, smaller spacing is required. This further improves either the accuracy or speed offered by direct slicing. As mentioned in section 4.3, direct slicing requires a slice format to be used and an alternative method of support generation is also needed. Materialise have provided a software tool [94] which can use several different slice formats, allows for slice checking and repair, automatically creates build supports from slice data and facilitates conversion from STL to a slice format.

4.2.4 Process Planning

In terms of the automatic selection of optimum process parameters, much of the research has been in the area of optimising build orientation. Orientation algorithms have been developed by Allen and Dutta [95], Frank and Fadel [96], Kim et al [97], Cheng et al [98] and McClurkin and Rosen [99]. (The software developed by McClurkin and Rosen also considers layer thickness and laser hatch density as part of an overall build style optimisation.) The objective of these algorithms is to optimise one or more of the following objectives: support structures, build time, part accuracy, surface finish and trapped volumes.

Optimum build orientation has also been considered as an integral part of the total process planning strategy developed at BIBA in Germany [73]. The system being developed aims to accept and verify neutral format CAD data, to create triangulated and sliced data for RP from the CAD model, to accept and verify slice data in various formats, to automatically generate support structures and to select the most appropriate RP system and secondary process(es). A different integrated process planning strategy is being followed by the University of Michigan [100]. This system can accept several formats of slice data, create a solid model through the slices, optimise orientation, generate supports and output either a solid model or an STL file. It can be seen that these two systems aim to integrate many of the capabilities of the other software tools which have been described in the above sections.

4.2.5 Process Simulation

The cost of creating a model using RP can be very high. If a model is built using poorly selected process parameters, the outcome can be an overlong build time, or worse still, a flawed model. One strategy that helps to avoid this is simulation of the build process. If the computer simulation indicates a problem, process parameters can be reselected until an acceptable simulation result is obtained. This should reduce the number of poor builds and hence cut costs and time. At one level, simulation can involve build-time estimation which will help to determine the model cost and provide information for scheduling. Build-time estimators for Stereolithography have been developed by Yu and Noble [101] and Chen and Sullivan [102]. At a more sophisticated level, finite element analysis and computational fluid dynamics can be used to predict the amount of distortion, temperature distribution and material flow during the build process [103, 104, 105, 106, 107].

4.2.6 Integration of Software Tools

Many developments are afoot that have the aim of providing software tools to support the use of RP. Some of these tools are commercially available but most are at the research stage. Of course, the most important software tool to support RP has been commercially available for some time, i.e. surface and solid CAD modelling systems. The relationships between these various software tools are shown in Figure 4.2. It can be seen that these relationships are quite complex with several possible alternatives in their order of usage together with a requirement for feedback and iteration between different tools. There is a requirement for data representation and storage at many stages in the overall process. The use of independent data stores would lead to duplication and possible translation problems.

The use of the "stand-alone" software tools currently being developed (as represented by Figure 4.2) leads to a number of problems:-

1. Designers and/or RP operators are presented with a complex suite of programs and an uncertain process route through these.
2. Data is duplicated and data translation errors can occur.
3. There is no automatic feedback to designers.

To avoid these problems, it is essential that an integrated approach is taken in terms of data representation. This would enable all of the software tools to work from the same database. A single user interface should be used to act as an "umbrella system" for the tools and to lead the user through them in the correct order. As each tool is used, the data it creates would be added to the database. In this way, feedback is automatically provided to the designer who would have continual access to the database. Such a collection of integrated software tools which provided a range of RP support facilities for the designer and RP operator could be termed a "design support system for RP".

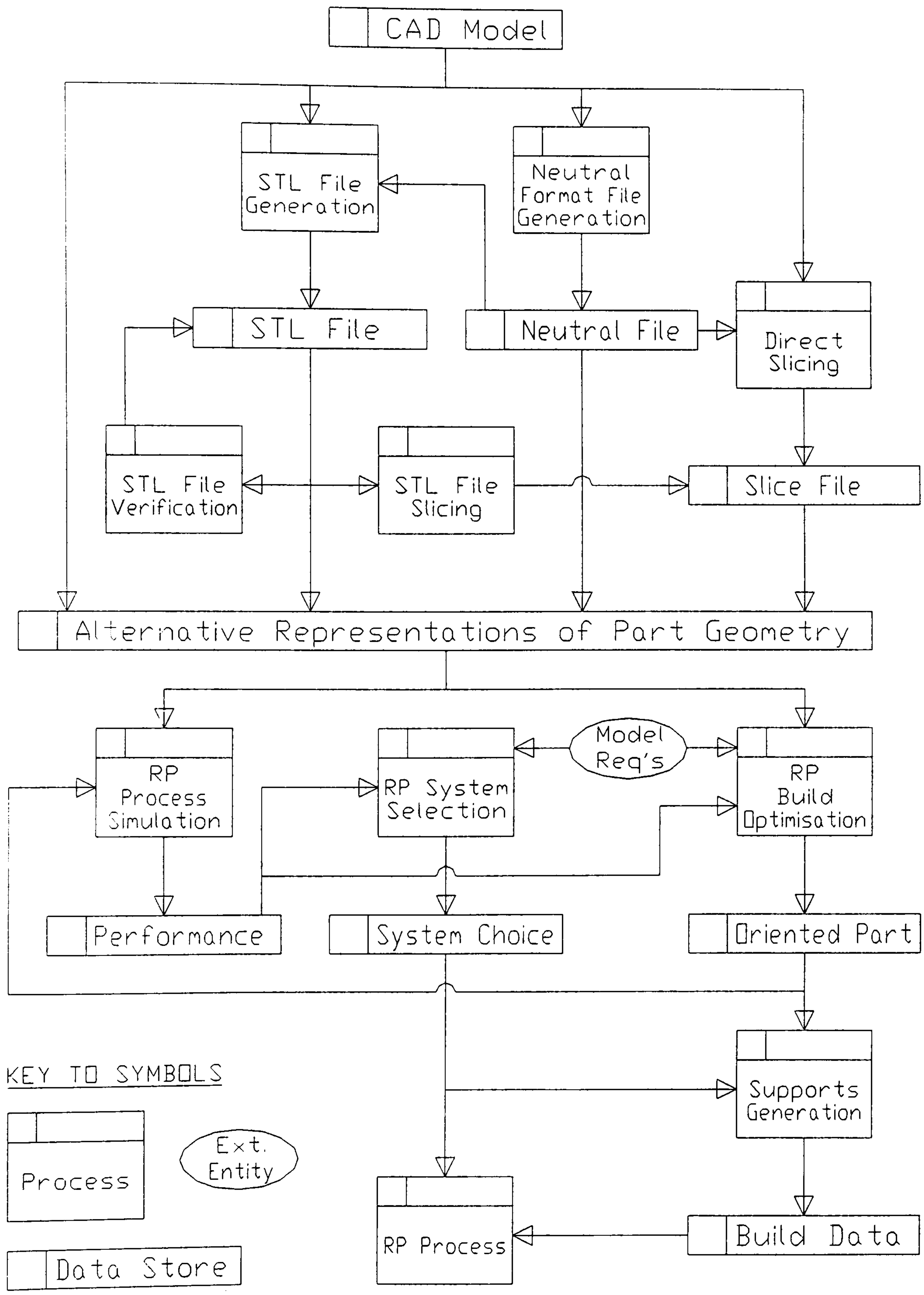


Figure 4.2 Relationship between various RP software tools.

The closest that any of the previously discussed tools get to being a complete design support system is the overall process planning system being developed at BIBA [73]. A common data structure has been envisaged for this system which will represent the geometry of the part(s) to be made using RP. This highlights a failure common to all of the tools discussed above, i.e. concentrating upon the geometric aspects of the design alone. During the design process, many other types of information besides geometry are created and used. These will have an impact on how RP should be used. Therefore, a truly integrated design support system for RP, should cater for the use of non-geometric information as well as part geometry.

The need for this "product model" driven approach has been recognised by Carleberg [108] who has proposed using STEP application protocol AP204 [109] to represent both a part's geometry and the process parameters required to drive an RP system. The use of a STEP application protocol has also been recommended by Steger et al [110] who comment that this would enable product data including geometry, topology, features, materials and tolerances to be used for planning and production of prototypes. It is this author's opinion that a product model incorporating all relevant design information must be used to support the whole range of RP software tools from system selection to process simulation.

4.3 Requirement Statement

Chapter 2 has shown that engineering design is a complex and iterative process that has been helped immensely by the adoption of computerised tools. Integration of design with downstream processes is desirable and feature-based design offers great potential in this area. Chapter 3 described the expanding range of RP technologies and applications. This expansion is enabling RP to play a greater role in the design process, and the future impact upon the designer will be substantial. For these reasons, it should be treated as an inherent part of the design process. In this chapter, the need for an RP system to be used effectively has been discussed. This requires RP to be used only when appropriate, the most suitable RP system to be selected, a comprehensive data exchange from CAD to RP and the optimisation of RP process parameters for individual models. It is likely that RP will be used several times during the design process, each time with different model requirements. Failure to recognise the necessary steps for effective use of RP will result in a weakened link between design and RP. The review of the RP software tools shows that major failings common to nearly all of them are their lack of integration and their concentration upon geometric data alone. A "product model" approach offers the potential to overcome these weaknesses by using all relevant design information to optimise the use of RP.

Therefore, a "requirement statement" was formulated to provide an end goal for this research:-

> The effective use of RP requires the use of a "design support system for rapid prototyping". Such a system must be used throughout the design process, whenever the use of RP is contemplated. The system must ensure that all relevant design

information is used to optimise each task in the application of RP, from deciding whether or not to use RP to the selection of process parameters. Therefore, a product model which can incorporate both geometry and other design information is required. A feature-based design approach has the potential for providing this comprehensive product model.

The development, implementation and evaluation of a design support system for rapid prototyping are the subjects of the remainder of this thesis.

CHAPTER FIVE

DEVELOPING THE SPECIFICATION FOR A DESIGN SUPPORT SYSTEM FOR RAPID PROTOTYPING

There have been several attempts to promote the need to take the proposed use of RP into account during the design process. CAD considerations such as the requirement for a fully enclosed surface or solid model have been discussed in detail [111]. The impact of using RP on the total design process has also been discussed [112, 113]. These authors conclude that RP can be used to improve the whole product development process. Therefore, the designer should not simply produce a CAD model which meets the design specification and then pass this on to the RP service. This treats RP as a "bolt-on" to the design process rather than an integral part of it. Besides, this "over-the-wall" mentality runs totally contrary to the concurrent engineering philosophy that RP is often used to support. This author argues that a design support system (DSS) which embodies a "design for rapid prototyping" methodology is required to integrate RP into the design process. For some time now the need for such a methodology has been recognised [114, 115, 116] but remains unsatisfied.

5.1 The Need for a Design Methodology which Supports the Use of RP

It could easily be argued that asking a designer to take RP into account during the design process is imposing an unnecessary constraint upon the design. Many constraints besides functionality already exist, e.g. design to cost, design to schedule, design for quality, design for manufacture, design for reliability, etc. To add yet another, simply to facilitate the model-making process, must surely be undesirable.

If RP was still limited to producing prototypes then this attitude would be justified. However, rapid prototyping has developed into rapid tooling and even rapid manufacturing. RP is no longer just a quick way of making models, but rather a new set of manufacturing processes that can be used either directly or indirectly (through secondary processes) to produce finished parts. Consequently, it should receive the same consideration during the design process as more traditional manufacturing techniques. The most effective way of achieving this is to give designers a methodological approach to follow when considering the use of RP. Such a methodology must overcome all the problems associated with ignoring the downstream use of RP. It must also allow for the fact that the use of RP can sometimes change the design process, e.g. the use of a physical model to replace detailed drawings or CAD images during design review meetings. The most effective way of applying the methodology is through a computerised design support system.

5.2 Problems Caused by Not Considering RP during the Design Process

If RP is treated as a "bolt-on" process, i.e. the CAD model is first completed and then passed on to the RP service with little discussion, a range of problems can occur.

5.2.1 Unsuitable RP System Selected

One potential problem is that the most suitable RP technique will not be recognised. The range of commercially available RP techniques is continually widening. Each technique has its own particular characteristics and capabilities. An essential part of a DSS will be to guide the designer in the choice of which technique to use. This decision will depend on several factors including the size and shape of the product, its desired material properties and the uses to which the RP model will be put. Therefore the DSS must enable the designer to match the needs of the design with the capabilities of the RP techniques available.

5.2.2 Design is Difficult to Produce Using RP

A design could be created in such a way as to make it unnecessarily difficult to construct using RP. This will incur extra cost and time during the RP process which tends to negate some of its benefits. Each RP technique has its own specific requirements. For example, some systems have great problems producing "trapped volumes", i.e. volumes of space within the model which have restricted access. This can sometimes be avoided by building the model in several stages. Alternatively, the design can be altered to eliminate the trapped volume. The CAD model must therefore be tailored to the RP process that is being used. If the RP service is given a CAD model that is unsuitable then either it will have to be returned for modification or altered by the RP system operator. Both these remedies are undesirable because they add extra lead-time into the product development cycle. Also, the latter alternative may lead to an accidental loss of the designer's intent. If the design is not altered then a less than optimum model will be created. Therefore the DSS must ensure that the designer is aware of the implication of the design upon the RP process.

5.2.3 RP Model does not Meet Requirements

Designers normally use RP when they have a specific application for the RP model to perform e.g. it may be for design verification, test and analysis or to facilitate the production of tooling. In each case, the RP model must be capable of meeting the requirements that the designer has in mind. If it does not, this will result in a wasted RP model, increased cost and time, and dissatisfaction with the RP process. Possible causes of an unsuitable RP model are poor surface finish, insufficient accuracy and wrong material specification. It is desirable for the RP model to be right first time. This can only be achieved if all the necessary information on model requirements is communicated from the designer to the RP service. Therefore, the DSS must ensure that this information is produced and made readily available.

5.2.4 Designer is Unaware of New Possibilities

The final problem that could be encountered is that an opportunity to improve the design process using RP is overlooked. New manufacturing possibilities are being realised by RP techniques. Not only can prototypes, tooling and final products be created directly from a CAD model, but also products that were previously difficult or impossible to manufacture are now becoming feasible. A trivial example of this is the internal staircase in the model castle shown in Figure 5.1. A more useful application is in the realm of microfabrication as described by Burns [117]. Using RP techniques, microfabrication can create electromechanical systems that are only a few microns in size. Designers must be encouraged to make use of these new possibilities.

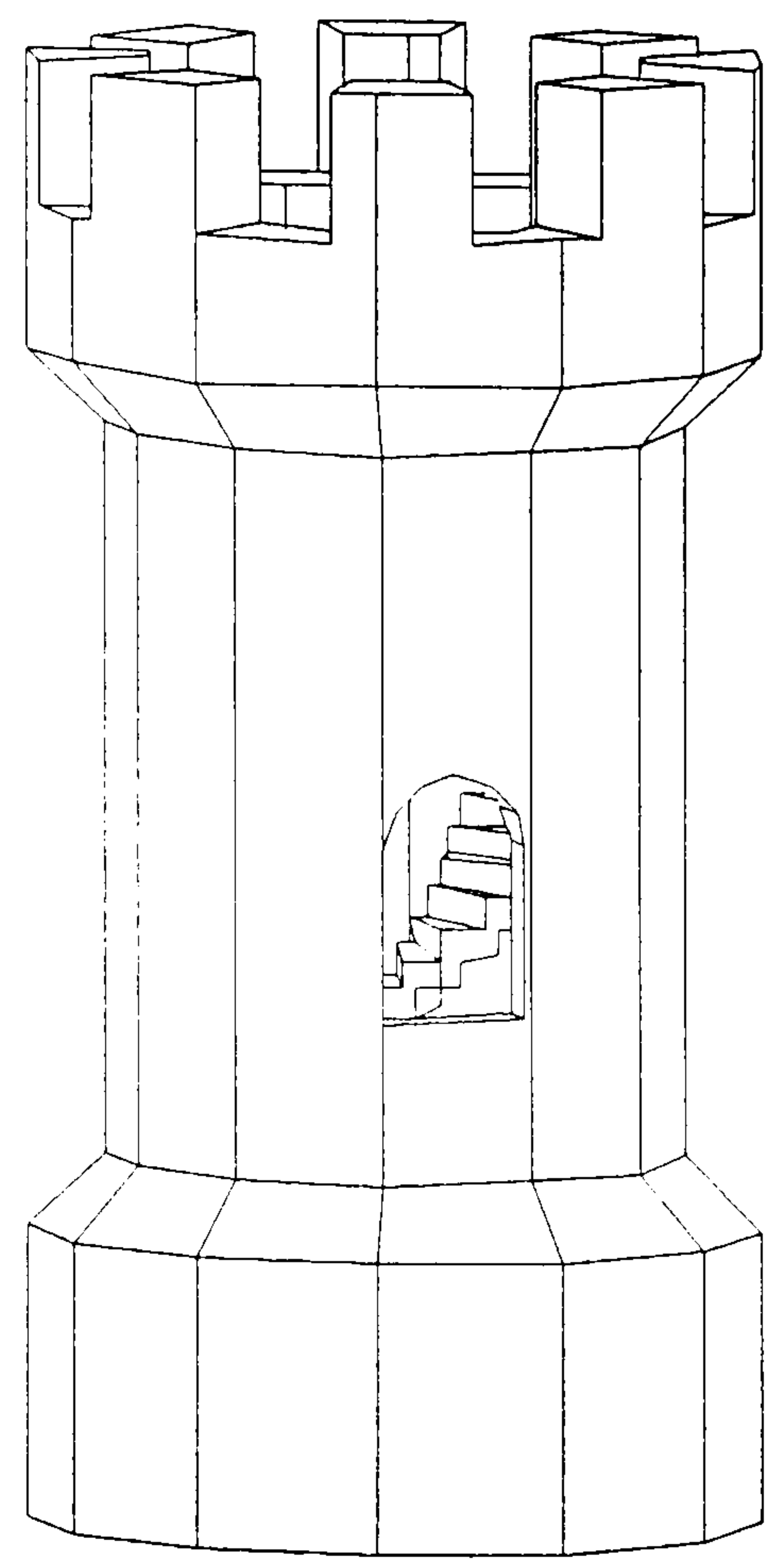


Figure 5.1 CAD model of a castle with internal staircase.

Increasingly, designers will have access to several RP techniques and will need to be aware of the design implications of using each one. In order to avoid potential problems and exploit new capabilities, a DSS which enables them to follow a methodology giving full consideration to RP is a necessity.

5.3 Determining Designers' Requirements for a DSS for RP

Before the DSS could be developed, it was necessary to determine the designers' requirements it would have to meet and then use these to create a specification for how it would function. This was achieved by conducting a survey of designers who have made use of RP. The survey was designed to ascertain how the designers used RP, what benefits they had seen, any problems that had been encountered and what they would like to see happening in the future. Many of the potential problems (as listed in section 5.2) had already been identified but it was important that these were corroborated by evidence from the "field". Likewise, the author had his own ideas about what future improvements needed to be made in the link between design and RP but these had to be supported by wider opinion to make a strong argument for implementing them.

The process used to determine which questions should be asked during the survey was one of conception, evaluation and improvement. It was decided that the survey of designers using RP should follow the four steps deemed necessary for the effective use of RP as discussed in Chapter 4. This would enable the results from the survey to be used to support the development of a DSS which embodied these four steps. Therefore, an initial series of questions was conceived by applying the author's own design experience to each of the four steps. Some general questions on the design environment were also produced. These questions were evaluated by one of the author's colleagues who had more experience in the use of RP. Several shortcomings were identified and improvements suggested. These were used to develop a new series of questions which were used as the basis for a structured interview with the CAD System Manager of a company which was making regular use of RP [118]. During this interview, any questions which were ambiguous, unnecessary or which needed to be expanded were identified. Also, several questions were added and the structure of the list of questions was modified.

Finally, to check the validity of the survey questions, another structured interview was conducted using the revised series of questions [119]. This progressed without any problems and so it was decided to go ahead with a larger scale survey of designers using RP. The survey took the form of a questionnaire which was sent out to 55 people in 49 companies. The companies were selected from three sources:- a) members of the Centre for Rapid Prototyping in Manufacturing at Nottingham University, b) members of the UK Stereolithography Users Group and c) members of the UK Rapid Prototyping and Manufacturing Association. The final form of the questions used for the questionnaire is shown in Appendix A.

5.4 Results and Analysis of the Survey of Designers

Completed questionnaires were received from 26 people in 23 companies. One of these was unusable since the company had not yet used RP although they were intending to do so in the near future. Therefore, the usable response rate was just over 45%. The full results of the survey are shown in Appendix B but a summary is given here under the headings used in the questionnaire. Throughout this summary, all specific requirements identified from the survey have been highlighted by using **bold text**.

5.4.1 General Information

There was a wide range of company sizes and number of designers in these companies. The companies represented many different sectors of industry but over 50% came from the aerospace, automotive or electrical goods sectors. Therefore, the DSS will have to cater for this diversity. The vast majority of respondents (over 80%) were practising designers or engineering managers who were closely involved with the use of RP models.

5.4.2 Use of RP

Most respondents (56%) had heard of RP through Magazine articles or from colleagues. Almost half (48%) had started to use RP because it could help them reduce lead-times. Therefore, it is important that **the DSS does not slow the design process in any way**, preferably the opposite would be true. However, many other reasons for adopting RP were also stated. The most common criteria by far in the decision to use RP were project timing, cost and model complexity. However, once again, many other criteria were stated. There were many reasons stated for not using RP but only one of these (part too simple to justify use of RP) was quoted by more than three respondents. **The DSS needs to guide designers as to what types of component are suitable for RP**.

There was a wide variation in the number of models made in the last year from under five to over 100. The leading functions that these models were put to were form and fit analysis, sales/customer studies and design approval. Only 24% of respondents stated that a lack of availability of RP would have stopped them from producing models. This is reflected in the fact that most respondents (68%) still make use of other model-making techniques. This shows that most companies are not using RP to expand the role of models in the design process. However, this is one area where RP has a lot to offer, especially as an aid to concurrent engineering. **The DSS must enable designers to identify every possible use of RP in the**

design process and then they can go on to evaluate the appropriateness of using it. There was a wide range in the proportion of models made using RP from less than 10% to 100%.

The most common criteria for assessing the quality of RP models were accuracy (quoted by 64% of respondents) and surface finish (52%) with several respondents quoting both. However, many other criteria were also quoted. These criteria need to be stated by the designer and values placed upon each one. A majority of respondents (60%) had been satisfied by the quality of over 90% of their RP models. Every respondent was at least able to say that they had been satisfied with "most" of their models. There were many reasons stated for poor model quality. The only two which were quoted by more than three respondents were poor accuracy and poor finishing of model. **The quality of each RP model needs to be evaluated against the criteria specified by the designer**. In this way, unsatisfactory models would be prevented from reaching the designer, thus increasing confidence in the RP process.

The most important benefits of using RP were quoted as speed by 76% of respondents, cost reduction by 20% and design verification by 16%. Many other benefits were also quoted and several respondents stated more than one benefit. The most often quoted problems encountered when using RP were durability of models (16%) and unsatisfactory accuracy (12%). However, most respondents had had no major problems. Part of these problems may lie in unrealistic expectations by the designer. **The DSS must indicate to designers what capabilities they can expect with confidence from RP**.

5.4.3 Secondary Processing of RP Models

Every one of the respondents had used RP models for secondary processing. Vacuum casting was the most commonly used process (72% of respondents had used it) with investment casting the next most popular (44%). Spray metal tooling and direct tooling for wax parts had also been used. The majority (68%) of respondents had not used RP models to create prototype tooling but over half of these had considered doing so. All designers should at least consider using RP to aid the creation of prototype or even production tooling.

5.4.4 Effect of RP upon Design Process

The responses to the survey indicated that RP is being used throughout the design process with 20% using it for concept design, 20% for development after layout design had been completed, 16% using it prior to committing to tooling, 8% at the end of the design process prior to production and 36% using it at several of these stages. This is encouraging and **the DSS must aim to further promote the effective use of RP at all stages in the design process**. While only 52% of respondents had used RP to evaluate alternative designs, the vast majority (96%) had used feedback from RP models to make design modifications. Again, it seems that many designers are not making use of RP to its full potential. Once a concept design has been chosen, modifications to it are likely to be minor. If it is not the optimum design then extra cost and lead-time will be incurred and profits reduced. RP should be used to aid the designer in selecting the optimum concept design.

Similarity, 60% of respondents stated that RP had changed their design process while 76% saw it as an essential part of the design process for at least some of their products. The only change to the design process that was quoted by more than one respondent was an increase in the usage of 3D CAD (20%). Other changes listed included earlier verification of design, earlier discussions with toolmakers and the ability to design more complex shaped products. Each designer needs to determine how RP can increase the overall effectiveness of the design process, rather than simply speeding up parts of it.

5.4.5 Choice of RP System

Every one of the respondents had access to Stereolithography while no other system was available to more than 32% of respondents. This meant that in 20% of cases, no choice of RP system was available. In 40% of cases, the choice of system was made by the designer, in 36% of cases by someone else in the company (e.g. CADCAM Manager, Project Manager) and in the remaining 4% by the RP service supplier. The most commonly stated criteria for selecting the RP system were the end use of the model (24% of respondents) and cost/timing considerations (16%). Other criteria included surface finish, accuracy and strength of the model. In 68% of cases the required accuracy, surface finish and material for the RP model were decided upon by the designer. In a further 12% the decision was made jointly between the designer and the RP service supplier or model shop manager. **The designer needs to be provided with a method of selecting the most suitable RP system given the particular selection criteria to be used.**

5.4.6 CAD System

Many CAD systems were listed with several respondents using more than one system. However, the most commonly used systems by a sizable margin were AutoCAD and Unigraphics (both used by 32% of respondents) and Pro-Engineer (used by 28%). 80% of respondents were using CAD for over 90% of their design work. Almost all of the respondents (92%) had access to a CAD system with solid modelling capability but there was a wide range in the proportion of work undertaken using this capability (from less than 20% to 100%). Most respondents (64%) had access to a CAD system with FBD capability and of these, all but one were making use of this capability. Only 28% of respondents were sure that their CAD systems could attach non-geometric information to features and less than half of these were using this capability. Therefore, the DSS can start with the assumption that most designers are using solids and that many have FBD capability. However, the use of a CAD model to represent non-geometric data cannot be assumed.

5.4.7 Transferring Data to RP System

STL was the leading file format for transferring data from CAD to RP (used by 40% of respondents). The remaining 60% used either a neutral CAD exchange format, an actual CAD file or a 2D drawing. Over half of respondents (52%) had experienced no problems with transferring data but problems that were listed included poor STL files, incompatability of systems, lost data and over-large file sizes. These problems were overcome by some sort of reworking of the data. These problems must be avoided in every case to avoid time-consuming repetition.

Only 24% of respondents stated that they sent no information other than geometry to the RP service supplier. Other information transferred included 2D drawings, number of models required, material requirements, timescale requirements, required surface finish, required accuracy, layer thickness and preferred orientation. This information was sent in a variety of ways including by telephone, email, post and modem. **Designers must be encouraged to send this data in the most suitable format and using the most reliable medium.**

5.4.8 Relationship with RP Service

64% of respodents were using a RP bureau service, 20 were using facilities owned by their parent company and the remaining 16% had their own in-house RP facility. The length of time that RP had been used varied from less than one year to over five years. Most respondents (76%) received feedback from the RP service supplier but this was usually only if a problem was being encountered and when the model would be ready. However 12% of respondents stated that they had been given advice as to how the model could be changed to facilitate RP. 60% of respondents stated that their relationship with the RP service supplier was one of partnership. Only 20% described it as an "over-the-wall" relationship. **The DSS needs to assist designers in forming a partnership with their RP service supplier.**

5.4.9 Future use of RP

72% of respondents could foresee new applications of RP within their company and all of them expected to see an increase in the usage of RP. Rapid tooling was the most commonly quoted new application (44% of respondents). Designers need to be encouraged to actively look for new applications of RP. Most respondents (64%) saw no barriers to wider use of RP but those barriers which were listed included cost of RP models (quoted by 28% of respondents), lack of solid modelling capability, unacceptable lead-times, lack of management understanding and poor quality of RP models (all quoted by 12% of respondents or less). These barriers must be broken down. The use of RP could be made easier for the designer by reducing its cost (20% of respondents), introducing a desk-top RP system (12%) and through a number of other actions. Finally, all but one of the respondents aims to keep abreast of new RP developments, mainly through literature and conferences. **This function may also be provided by the DSS by giving designers an up-to-date list of currently available RP technologies**.

5.4.10 Conclusions from Survey

Most designers concluded that RP had both changed the design process and had become an essential part of it. However, the changes to the design process that were listed were mainly fairly trivial. Those companies which have used RP to radically alter their design process have seen most benefits. This is because RP has been used to open up new possibilities rather than replicate existing practices. It is desirable that RP is used in an imaginative way to aid as many stages of the design process as possible. One such usage of RP models is as a new means of communication which is 3D in nature and understandable by a wide range of personnel [28].

In terms of the future use of RP it was interesting to note that most designers foresee both a greater usage of RP and a wider range of applications. It is logical to assume that in future years, more designers will be making use of RP for a wider range of applications. Designers need to be made aware of what applications RP can be used for.

The overall conclusion to draw from the survey is that most designers are happy with their current use of RP. It could be argued that there should be no attempt to "fix what is not broken". However, many problems were identified including:-

1. RP is not being used to expand the role of physical models
2. 40% of designers were not satisfied with at least 10% of RP models
3. RP is not being used to its full potential by many designers
4. Most designers do not attach non-geometric data to CAD models
5. Data transfer problems have been experienced by almost half of designers
6. Feedback from RP services is very limited

All of these are attributable, at least in part, to a weak link between design and RP, either in the procedure for using RP or in supporting software. Designers who have been using RP for some time may have learnt how to overcome many of these problems but it would be preferable for them to be avoided in the first case. Therefore, there is a strong case for new RP users to be given the ability to learn from the experience of existing users, i.e. to adopt best practice. Also, it should always be the aim of any RP user to continuously improve the way they use the technology. The designers' requirements which have been derived from the questionnaire indicate the necessity of improving the link between design and RP by eliminating existing problems and by increasing integration.

5.5 Aim of the DSS for RP

Drawing upon the previous sections, it is possible to define the overall aim of the DSS as follows:-

> To integrate RP into the design process in order to maximise its effectiveness.

This raises the question as to what the terms "integrate" and "effectiveness" mean. The precise definition of these terms will be clarified within the remainder of this chapter.

5.6 Characteristics of the DSS for RP

The overall aim of the DSS was expanded into ideal system characteristics (which can be used as performance measures) using a matrix approach, similar to that used within the quality function deployment process (see Figure 5.2). The designers' requirements obtained from the questionnaire results are listed down the left-hand side of the matrix and characteristics of a DSS needed to meet them are listed along the top. The correlations between requirements and characteristics are shown by crosses entered in the matrix.

	System Characteristics						
Designers' Requirements	Make RP an integral part of design process	Enable designer to consider use of RP at any stage in design process	Avoid the use of RP in unsuitable circumstances	Ensure right first time RP models	Ensure the correct choice of RP process	Improve communication between designer and RP operator	Optimise RP build parameters
Must not slow design process	x			x			
Suitability of component for RP			x				
Identify possible uses of RP		x					
Quality assessment of RP models				x			
Indicate RP system capabilites						x	
Promote use of RP at all stages of design	x	x					
Enable selection of most suitable RP system					x		x
Encourage use of best data format						x	
Assist partnership with RP service						x	
Provide up to date list of RP technologies			x				

Figure 5.2 Correlation matrix between designers' requirements and system characteristics.

The characteristics would provide both the starting point for system definition and a yardstick against which system performance could be measured. Each characteristic is described in detail below.

5.6.1 Make RP an Integral Part of the Design Process

An ultimate aim of some RP researchers and vendors is to provide the designer with a "desktop manufacturing" system or a "three dimensional printer". This is reflected in the names given to some of the commercially available systems and the companies that sell them. This would involve the designer, sitting at a CAD terminal, invoking a menu option that would create a 3D hard copy of the model on the screen, in much the same way as a 2D plot can be requested today. The model could then be used for visualisation or for any downstream process such as analysis or tooling manufacture. This would be the ultimate in integration of RP into the design process. Indeed, several designers referred to this possibility within the survey.

However, current RP systems are some way from providing this service. One reason for this is that the operation of an RP machine is a skilled task, requiring an experienced person to select the optimum process parameters. Another reason is that the transfer of data from CAD to RP may require some manual intervention to check and repair exchange files. A third reason is that no single RP machine can offer an unlimited capability in terms of material, accuracy or speed. Therefore, the conversion of a 3D CAD model into a 3D physical model is by no means fully automated. The challenge for the DSS is to make the transition from CAD model to RP model as easy and reliable as possible. This could be referred to as providing a "virtual" desktop RP system since this is how it would appear to the designer.

5.6.2 Enable the Designer to Consider the use of RP at any Stage in the Design Process

The use of RP can yield benefits at many stages in the design process. However, the function of the RP models and the amount of design information available will vary throughout the process. Therefore, the DSS must be flexible enough to cater for any function which the model may be used for and to make use of whatever design information is available. If a totally inadequate level of information is available, the designer must be prompted to provide the extra information required. Only then can the appropriateness of using RP be decided upon.

5.6.3 Avoid the use of RP in Unsuitable Circumstances

RP process time is a scarce commodity like any other and should not be used in a profligate manner. Its unnecessary use must be avoided by ensuring that RP is the most suitable method of creating the physical model. Other model-making techniques exist such as hand-crafting, conventional and CNC machining. The most appropriate technique in any specific case will depend on the geometry of the component, the material requirements, the desired accuracy and so on. It is essential to determine if the use of RP will save time or money, or indeed if its use is practical. A fundamental characteristic of the DSS must be that it enables the designer to identify when other model-making techniques would be more appropriate.

5.6.4 Ensure Right First Time RP Models

Creating RP models is a costly process for several reasons:- RP machines are often expensive and depreciation costs must be added to build costs; RP materials are often expensive e.g. photosensitive resins; some RP processes must be supervised hence adding the cost of operator's time; if pre-processing of CAD data is required, this is a skilled task and adds considerably to the cost of the model. Also, although the actual build time for an RP model is typically a matter of hours, the total turn around time from CAD model to physical model is typically one to two weeks [120]. Therefore, the result of an RP model which does not meet the designer's requirements is a waste of money, and perhaps more importantly, a waste of valuable lead-time. One of the key characteristics of the DSS must be to ensure that RP models are right first time, i.e. fit for the purpose the designer has in mind.

Several factors must be in place for this to happen. The most suitable RP process must be used, all relevant information must be made available to the RP operator and the correct build parameters must be selected for the RP process. Each of these factors lead directly to the following characteristics which the DSS must also have:-

5.6.5 Ensure the Correct Choice of RP Process

The number of RP processes is growing continuously, offering a wider range of possibilities to the designer. The DSS must provide the designer with a robust procedure whereby the optimum RP process for a particular component can be established.

5.6.6 Improve Communication between the Designer and RP Operator

The DSS must ensure that all relevant information is transferred from the designer to the RP operator in the most suitable format, and at the right time. This will ensure that the RP operator has a clear understanding of the designer's requirements from the RP model and that the data pre-processing time is minimised.

5.6.7 Optimise RP Build Parameters

Most of the build parameters will be selected by the experienced RP operator. However, there are some, such as model orientation and layer thickness which the designer may want to specify. The DSS must provide designers with a list of build parameters for each RP process and allow them to select values for any which they see as critical to the performance of the RP model. The effect of these choices must be conveyed to the designer. For example, if the designer wishes to investigate the effect of a certain build orientation on the surface finish of a critical feature, the influence upon build time and cost must also be evaluated. This should allow the optimum compromise between the factors of cost, time and surface finish to be reached.

5.7 Conclusions

The survey of engineering designers using RP confirmed the need for a design support system for RP which would improve the link between design and RP. The designers' requirements, identified through analysis of the questionnaire results, had been translated into ideal system characteristics. The next stage of the project was to define a system which would meet all of the requirements identified during the survey.

CHAPTER SIX

DEFINING THE DESIGN SUPPORT SYSTEM FOR RAPID PROTOTYPING

6.1 Objectives

The survey of designers using RP identified the overall aim of the DSS as being to integrate RP into the design process in order to maximise its effectiveness. Furthermore, the ideal characteristics of the DSS were derived from the designers' requirements obtained from the questionnaire:-

1. Make RP an integral part of the design process
2. Enable the designer to knowledgeably consider the use of RP at any stage in the design process
3. Avoid the use of RP in unsuitable circumstances
4. Ensure right first time RP models
5. Ensure the correct choice of RP process
6. Improve communication between the designer and RP operator
7. Optimise the RP build parameters

For a DSS to display all of these characteristics, it would have to give the designer access to all RP-relevant design information, enable this information to be applied to decisions about using RP and communicate this information to the RP service to allow them to provide high quality RP models. Only then will the designer have confidence that RP can be used effectively and that it should become an integral part of the design process

The questions that need to be answered in order to define the DSS are as follows:-

1. What design information is required to support RP?

2. What format should this information be in?

3. How will the information be used to make decisions about the use of RP?

These questions are answered in turn in the following sections.

6.2 Design Information Required to Support RP

Chapter 4 identified four steps which must be followed if RP is to be used effectively. Three of these are the responsibility of the designer, i.e. deciding if RP is appropriate (Step A), selecting the optimum RP process (Step B) and transferring the necessary data to the RP service (Step C). The decisions may be taken in consultation with the RP service. The survey of designers using RP was able to identify the type of information used at each of these three steps (see Table 6.1). It can be seen that some of the information is used for all three steps, some for two and some for only one of the steps. Most of the information is either part of the product design or else it can be derived from it. However, some information is not related to the design, e.g. the availability of RP resource. The design information required for RP could come from one of several sources. Much of the information would be contained in a comprehensive design specification as described by Pugh [121]. Additional cost and timing information would be in the design brief. However, tolerance and surface finish requirements would have to come from a detailed component drawing. This would not be available until after the concept design stage. In practice, the designer could make use of all these sources but this would have two drawbacks. Firstly, the designer would have to decide what information is relevant to RP and, secondly, the non-unified structure of the information would make it difficult to computerise the decision-making process.

Type of Information	Step A	Step B	Step C
Function of model	X	X	X
Lead-time requirement	X		X
Quantity of models	X		X
Cost of making model	X	X	
Complexity of model	X		
Project priority rating	X		
Model required for communication	X		
Customer requires model	X		
Overall dimensions of model	X		
Surface finish requirements		X	X
Required accuracy/tolerances		X	X
Required model material(s)		X	X
Build time for model		X	
Availability of RP resource		X	
Strength requirements		X	
Advice from RP operator		X	
Project cost code			X
Outline drawing of model			X
Preferred build orientation			X
Project brief			X
Secondary process requirements			X
Facetting accuracy for STL file			X
Solid or hollow part required			X
Layer thickness			X
Colour(s)			X
Critical dimensions			X
Datums			X

Table 6.1. Information required to support the use of RP.

6.3 Format of Information Required to Support RP

A method of storing all the information about a product throughout the whole of its design and manufacture process is known as "product modelling" [122]. The concept of product modelling is gaining acceptance and forms the basis for the development of the STEP international standard [123].

For some researchers, product modelling must make use of feature-based design (FBD) [124, 125]. This enables non-geometric information to be attached to the product model at a sub-component level. This would clearly be of benefit in supporting RP as some of the information in Table 6.1 could then be related to individual features of the model to be built, e.g. surface finish requirement, preferred build orientation, required accuracy. This would involve the use of feature-based design.

Kruth has claimed that RP eliminates the need for FBD [72]. The argument used is that the RP process does not need to be adapted for the type of feature being built. While it is certainly true that RP models can be built without the use of FBD, the non-geometric information associated with features can be used to optimise RP processes [126, 127]. Therefore, the DSS will make use of the product modelling concept and will incorporate the use of FBD.

6.3.1 Feature-based Design for Rapid Prototyping

There is an inherent problem associated with using features as part of a product model. Features have different meanings to different functions throughout the design and manufacturing process. For example, a designer will use features as the building blocks for a CAD model whereas a manufacturing engineer uses features to determine which processes to use. "Features ..... in a geometric model become context specific and highly dependent on the application that the model is used for." [128]. In other words, since features are used for different purposes, they need to contain different information. A product model tries to be comprehensive whereas features are application specific. How can this apparent contradiction be resolved?

A solution to this dilemma is to use multiple feature views and feature conversion [129]. Different versions of the same feature are held in the product model. Each function has its own view of the product model which gives it access to the features relevant to a specific application. Features for one application are related to features for another through conversion or "mapping". In this way the product model continues to meet all the requirements of the design and manufacturing process without having to use generalised features. Part of the function of the DSS must be to define what features mean with respect to RP and to determine what format should be used to store RP-related feature information. It would then be possible to map features defined in a CAD system into the features within the DSS.

6.3.2 Definition of Features for RP Applications

RP is used to create models which have the same shape as the electronic CAD model. Therefore, an important aspect of the features which will be used to support RP is how they represent shape. There are a number of different types of features which can be used to create shapes. These are closely related to the main representations used in solid modelling CAD systems, i.e. boundary representation (B-rep), constructive solid geometry (CSG) and halfspace representation [129]. Most RP models are created from CAD systems which use B-rep solid modellers, e.g. Pro-Engineer and Unigraphics. With B-rep, the solid object is defined by a set of faces, edges and vertices (called topology) which map onto surface and curve geometry (see Figure 6.1). This gives the advantage of being able to use complex freeform surfaces while still having the ability to construct models from volumetric primitives which are then incorporated into a B-rep format. Also, using B-rep it is possible to have either surface or volumetric features. This is particularly useful for RP where some information will relate to surfaces, e.g. surface finish, while other information will relate to volumes, e.g. required material. Using B-rep features, it is possible to attach non-geometric information to collections of surfaces which form a surface feature or a volumetric feature.

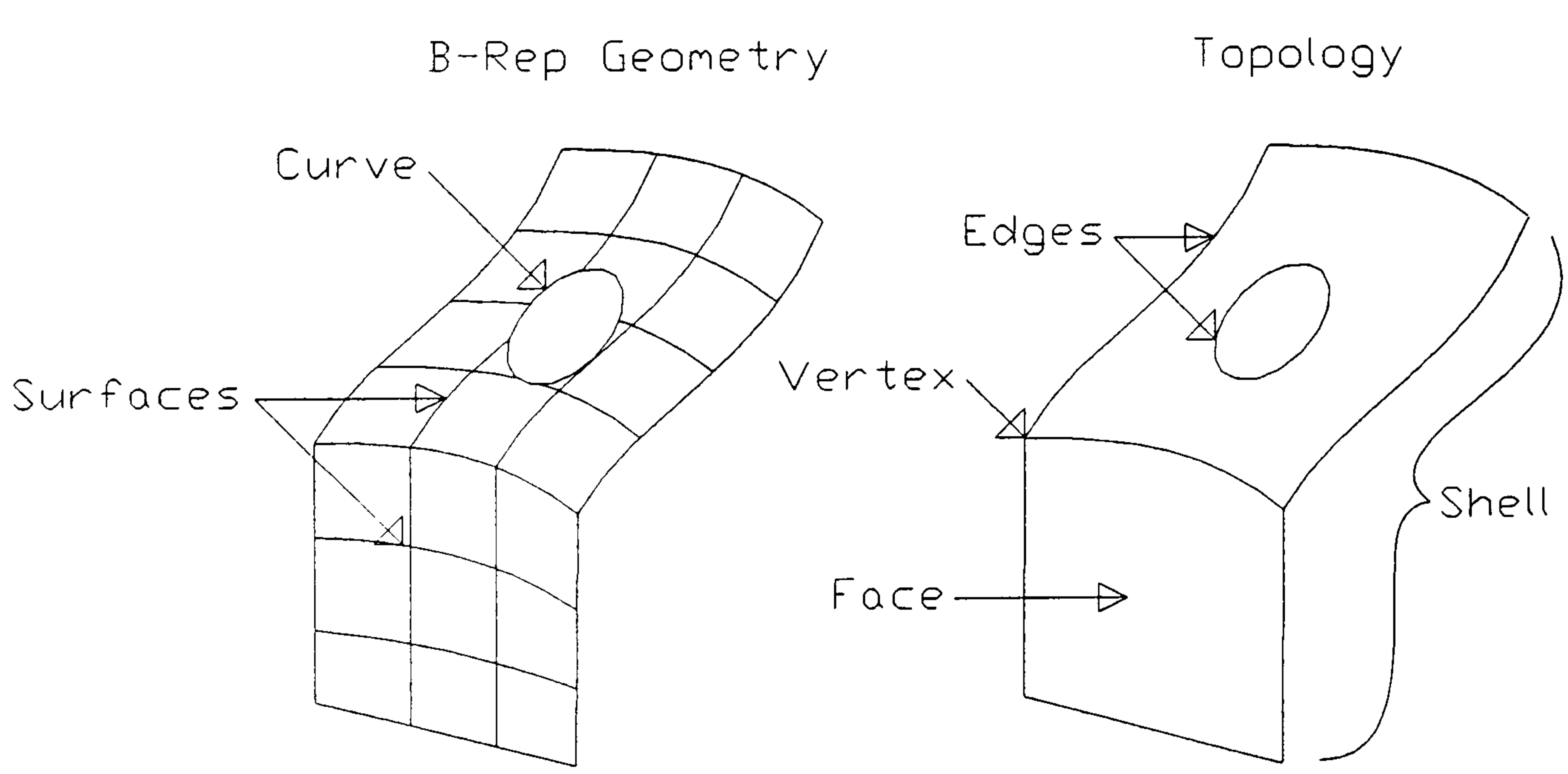
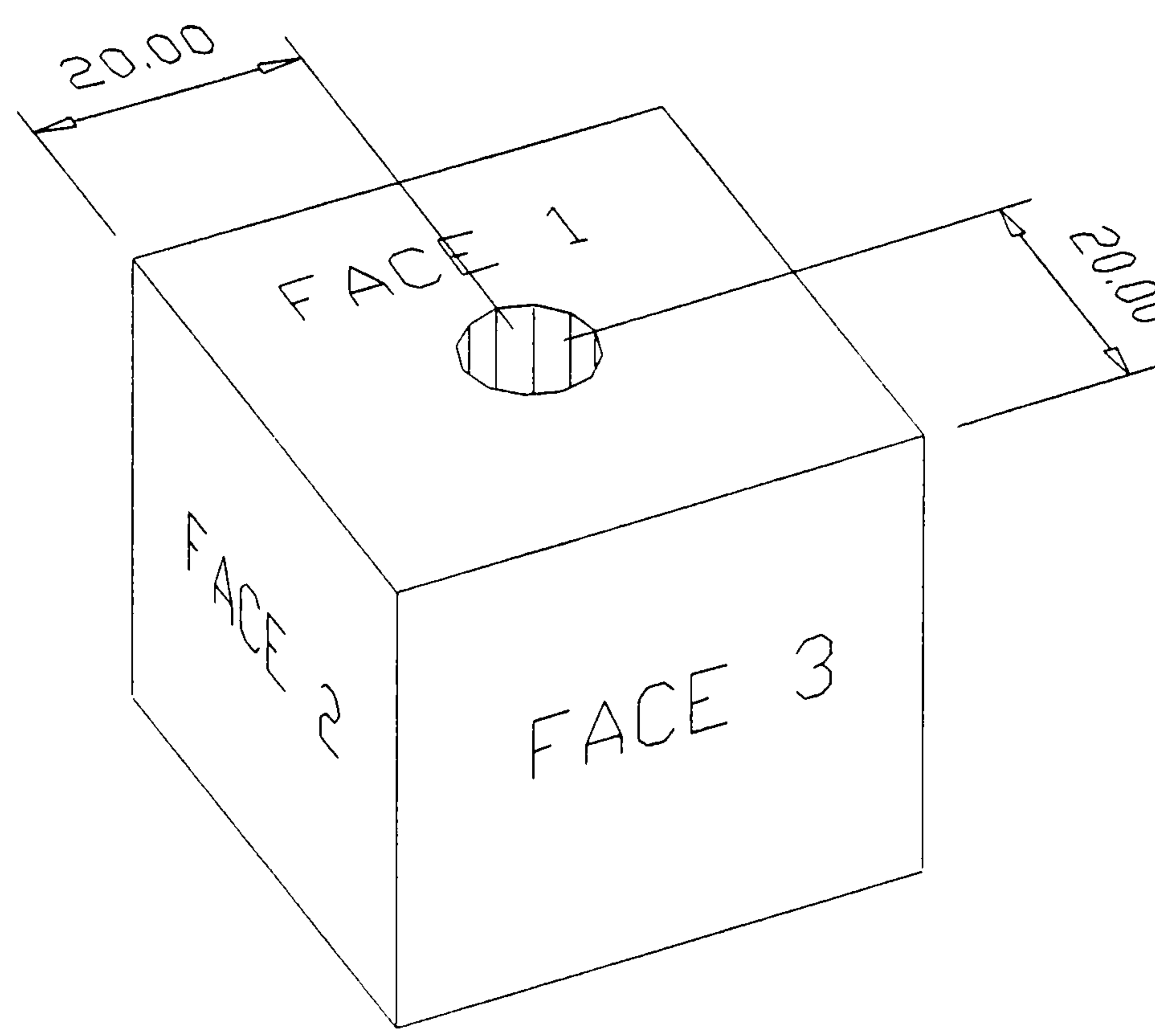


Figure 6.1 Example of B-rep geometry and associated topology.

It has been determined that the definition of a feature for RP applications must allow for either surface features or volume features. This allows total flexibility for the designer in deciding which shapes to attach information to. Examples of surface features would be chamfers, datum faces and styling surfaces. Volume features could include bosses, surface protrusions, stiffening webs and even the whole part itself. Negative volume features are not required since RP does not use material removal operations. The range of features that could be used to describe component geometries is extremely large. This means that it would be almost impossible to restrict the designer to a set of standard features. Rather, freedom to create user-defined features must be provided. Some commercially available CAD systems allow for this e.g. Pro-Engineer.

Once the designer has decided upon which feature shapes will be used in the design, the next stage is to create their geometry and attach non-geometric information to them. This information could include most of the items listed in Table 6.1. However, the designer would also be given the flexibility to attach other types of information which will be of benefit to the application of RP processes. An example of how this would be of benefit is described by Palm and Shafiee [130]. Not all the information may be available initially but more can be added as the design process proceeds. An example of a feature with its attached non-geometric information is shown in Figure 6.2. The items of information are known as attributes and each attribute has a value which could be numeric, textual or a combination of both.



Attribute	Value	Description
Feature_ID	10002	Unique identifier
Feature_Name	HOLE1	User-defined name
Feature_Type	BLIND_HOLE	Standard class of feature
Parent_ID	10001	Unique identifier of parent part
Loc_Face	1	Location face on parent feature
Dat_X_Face	2	X Datum face on parent feature
Dat_Y_Face	3	Y Datum face on parent feature
Orientation	0,0,1	X,Y,Z axis values
Position	20,20	Local X,Y co-ordinates
Diameter	10 mm	Hole diameter
Depth	20 mm	Hole depth
Surf_Fin	0.05 mm	Surface finish (RA)

Figure 6.2. Example of a feature with its associated attribute list.

6.3.3 Representing Features for Supporting RP

Before the DSS can be implemented, it is necessary to formally define how RP features will be represented. A formalised method for representing data structures is the EXPRESS language, used to define the STEP international standard.

EXPRESS is a textual conceptual schema language [131] and is defined within ISO 10303 [132]. Essentially, EXPRESS can be used to define the structure of the data which is to be used to support a STEP application. Indeed, all of the application protocols (AP's) which have been published as part of ISO 10303 have been defined using EXPRESS. The EXPRESS data structures can be mapped into actual data files following a set of rules also defined in STEP. Furthermore, they can be represented in a diagrammatic manner using a formal graphical notation subset of EXPRESS called EXPRESS-G. EXPRESS can be used to define any data structure required as part of a product model and many such structures are already available within STEP AP's.

It would be most fortuitous if an AP for RP had already been developed which made use of features. Unfortunately, no AP has been developed for RP nor is there an AP which allows for the use of features with associated non-geometric information [133]. However, an EXPRESS specification for data structures to support layered manufacturing was developed by Kennicott [134]. Many of the entities he used were "standard" entities taken from AP203 - Configuration Controlled Design (the STEP AP most widely supported by mechanical design CAD vendors) [135]. In addition, several entities unique to layered manufacturing had to be developed, e.g. "slice_model", "layer", "scan" and "layer_thickness". These were specifically tailored to supporting laser-based RP techniques. An entity called "specification" which allowed for the inclusion of material specification and surface finish requirements was also used. Moreover, this information could be attached to individual features in a part (called "shape_aspects"). This EXPRESS although non-standard and non-approved, provided a useful starting point from which a complete EXPRESS definition of data structures for RP could be developed.

To create a complete feature-based data structure definition for RP it was first of all necessary to consider the type of geometric and non-geometric information that needed to be represented. The geometric data required for RP would be stored in the form of B-rep solids. A part could be represented as a single solid or as several solids relating to different volumetric features. Groups of surfaces within the part could be linked together and defined as surface features. Non-geometric information could be attached to either type of feature. Other geometry that could be represented would include triangular facets (to allow compatibility with STL files) and contours created from slicing through the original solids and/or their facetted approximations. A further extension would be the capability of assigning RP process parameters to entities within the database.

A simplified EXPRESS-G diagrammatic representation of the required data structure is shown in Figure 6.3. The use of EXPRESS-G does not limit the definition of the DSS to being a STEP-based application. This is simply a useful way of representing the data structure which is required. However, the advantage of using STEP is that it is likely that this will become the standardised way of representing engineering data in the future.

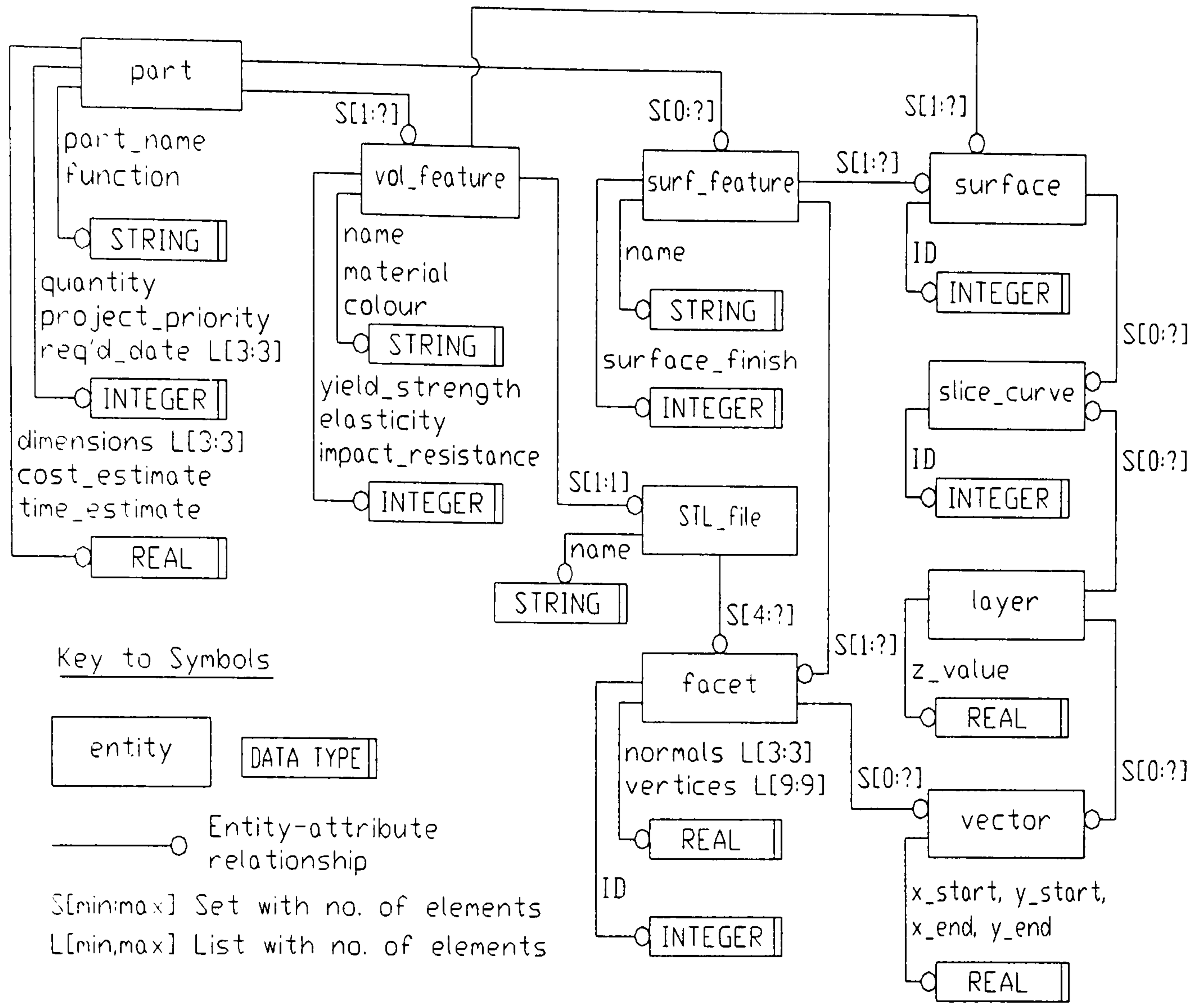


Figure 6.3 EXPRESS-G representation of the DSS for RP data structure.

6.4 Using Design Information to Support the use of RP

Having determined what design information is required to support RP and having decided to use EXPRESS-G to represent this information, it is now possible to consider how the information will be used. A number of factors have an important bearing upon this matter. Firstly, the data will not all be available at the start of the design process but will be added to as the design progresses. Secondly, the data (or subsets of it) will be used to make several different decisions regarding the use of RP. Thirdly, the data will be accessed by at least two different people (the designer and the RP operator) and possibly several others. Thus there is a requirement to create a data-sharing environment where data can be added to and selected from. This is where STEP again proves to be a useful tool. Within the ISO 10303 standard there is a class of parts referred to as Implementation Methods. An implementation method describes the way in which STEP data is to be shared amongst applications. Four levels of implementation have been identified to date [131]:-

1. Physical file exchange
2. Software assisted file exchange
3. Shared database
4. Intelligent knowledge-based systems

Currently, only the first three of these implementation methods are supported within ISO 10303. The most advanced of these, a shared database, offers many benefits compared to file exchange [136]. A single repository of product data can be accessed by several different applications, each one using all or part of the available information. An initial application (e.g. CAD) can generate the original information to populate the database and then this can be added to by subsequent applications. Multi-user access, a single copy of "master" data and improved security are further benefits.

6.5 Components of the Design Support System

Once the decision had been taken to use a shared database approach for the DSS, it was necessary to determine what the various components of the complete system would be. Again, a matrix approach was used (see Figure 6.4). This time, the ideal system characteristics from the matrix in Figure 5.2 were used to generate ideas for possible system components. The system characteristics are listed down the left-hand side of the matrix and components of the DSS are listed along the top. The correlations between characteristics and components are shown by crosses entered in the matrix.

	System Components									
System Characteristics	Shared database	CAD data input	Feature editor	RP usage advisor	Build time and cost estimator	RP system selector	Adaptive STL generator	Surface finish optimisor	Adaptive slicer	RP data output module
Make RP an integral part of design process	X	X	X							
Enable designer to consider use of RP at any stage in design process	X			X	X					
Avoid the use of RP in unsuitable circumstances	X			X	X					
Ensure right first time RP models	X	X				X	X	X	X	X
Ensure the correct choice of RP process	X				X	X				
Improve communication between designer and RP operator	X	X	X							X
Optimise RP build parameters	X						X	X	X	X

Figure 6.4 Correlation matrix between system characteristics and system components.

Obviously, the shared database is the most important part of the system and has a central role to play in the integration of design and RP and all the other characterisitcs. Much of the initial design data would be created using the CAD system. This would include geometry and possibly some non-geometric information as well. Extra design information relating to material specification, cost and timing constraints, desired surface finish, etc. could be added by the other software modules (see Figure 6.5). The identification of individual features could also be done within the CAD system. However, a potential problem with this approach is that STEP AP203 (the most commonly used application protocol for mechanical design) does not currently support features and transferring the information to the database might require a non-standard application protocol e.g. AP214 - Core Data for Automotive Design Processes. However, work is progressing to incorporate features within AP203 [133].

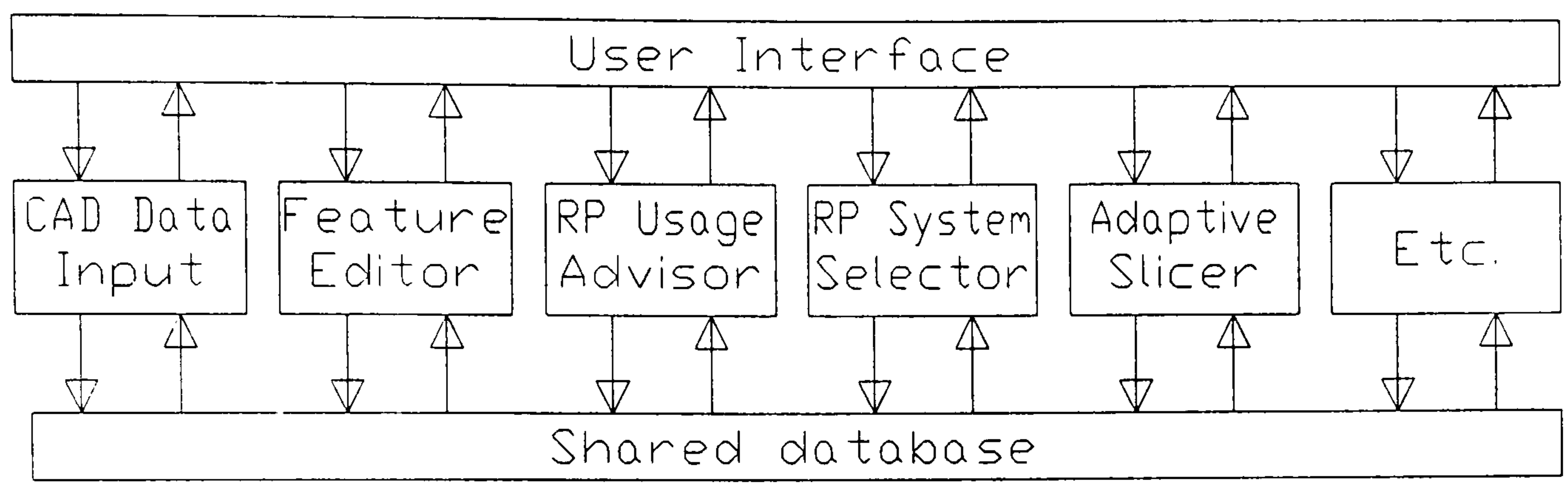


Figure 6.5. Using a shared database to integrate design and RP.

Since STEP has not yet been developed to a stage where it can directly support RP, it was decided not to make use of STEP definitions or files. However, the concept of a shared database is implementation-independent and is very suited to this area. Once all the design information required to support RP has been entered into the database, other applications could use this data for various RP-related tasks. A description of how each application would work and the data it would use and create are discussed in the following sub-sections.

6.5.1 CAD Data Input

The CAD system used must be capable of boundary representation solid modelling. Several commercial CAD systems meet these criteria including Pro-Engineer, Unigraphics, Catia and CADDS. The CAD model will be created using standard solid modelling commands and/or any FBD capabilities the selected system may have. Some CAD systems enable non-geometric information to be attached to features and this information could possibly be incorporated into an exchange file. More than one solid model may be required if the RP model is to consist of several volumetric regions with different properties such as colour or material.

Other functions which could be performed on the CAD system are the tessellation and/or sectioning of the model to create STL facets and slice contours respectively. The facets and contour segments would have to be associated with the surfaces from which they were created to be compatible with the EXPRESS definition described in Section 6.3.2. Once the CAD model is complete, it will be exported as an exchange file which in turn will be input to the shared database. This will create the geometric data in the database to which further information will be added.

6.5.2 Feature Editor

If the data which is transferred from the CAD system to the shared database is purely geometric, it will be necessary to identify features and attach non-geometric information to them. For volumetric features, this will be relatively straightforward. Different volumetric regions in a part will have been transferred as separate solid models and this will be reflected in the database. Attaching information to these features would simply involve accessing the database record associated with each solid model and entering values in additional fields.

Attaching information to surface features would be more problematic. This would require the surfaces in each feature to be identified and linked together. This is possible in some CAD systems where several surfaces can be "sewn" or "stitched" together to form an open shell. Such an open shell could be transferred via an exchange file. However, with other CAD systems this is not possible. It would be necessary to "tag" each surface which belongs to a surface feature and transfer a list of these surfaces to the database. Once this had been done, non-geometric information could be attached to the surface features in the same way as for volumetric features.

Therefore, the feature editing module would not only have to access the database records, but may also have to give the user access to a graphics package which would display the surfaces in the CAD model. After using the feature editor, all the design information relating to RP will have been entered into the shared database.

6.5.3 RP Usage Advisor

The role of the RP Usage Advisor would be to perform a "first pass" analysis on the suitability of using RP for a particular model in preference to other model-making technologies. The module would take its input from the user in the form of answers to a series of questions about the requirements and application of the model. These would include the number of models required, the importance of good surface finish and accuracy, and the general complexity of the model. These answers would be used to form a qualitative assessment of how likely it is that the use of RP would be beneficial. If the probability of RP being beneficial was low, no further analysis would be conducted.

6.5.4 RP Build Time and Cost Estimators

It is possible to arrive at a build time estimate for RP models using an algorithmic approach [137] or through the manipulation of system-specific build files [101, 102]. In both cases, certain information about the RP model requirements and the system capabilites is used to calculate the time needed to build the model using a particular RP technique. Build time has a large influence upon model cost and so a logical extension of a build time estimator is to predict the likely cost of building one or more models. Much of the information required for these estimations would be included in the product model for the component in question. The output from this module or modules would be a build time estimate in hours and a cost estimate in local currency.

6.5.5 RP System Selector

This module would be a more detailed "second pass" analysis of the comparative suitability of particular RP processes for the model to be built. It would use detailed information on model requirements together with the time and cost estimates from the previous module to arrive at a score for each available RP system. The relative importance of different user requirements would be catered for using a "weighting and rating" approach.

6.5.6 Adaptive STL Generator

This module would use the values of required tolerance for each surface feature to determine the meshing accuracy for the STL tessellation. This would allow larger facets to be used where a wide tolerance was specified and smaller facets where a tighter tolerance was required. In this way, it would be possible to create STL files which would meet the user's accuracy requirements and yet have less facets than when using a constant meshing accuracy.

6.5.7 Surface Finish Optimisation Module

Given a minimum slice thickness, the surface finish obtained on any surface feature of the RP model will depend heavily upon model orientation [138]. Therefore, for different model orientations, the required surface finish and predicted surface finish for each feature could be compared. The user could then select an orientation which gives the best overall achievement of surface finish requirements or one that ensures the best surface finish in a particularly critical part of the component. The output from this module would be X and Y rotation angles from the original orientation of the CAD model.

6.5.8 Adaptive Slicer

This module would use the values of required tolerance and surface finish for each surface feature to determine slice thickness. Different features could be created with different slice thicknesses yet still achieving the required accuracy and surface finish. The actual thicknesses of slices used would be limited by the RP technique being used. The thickness calculations would have to take the model orientation (as determined by the previous module) into account.

6.5.9 RP Data Output Module

The database would contain both the original design input data and new data generated by the various application modules. Much of this information would be useful to the RP operator to help in the selection of process parameters. Therefore, it would be beneficial to have a module which would output the required information in a useful format, either as a database table, a text file or some other common format. The module would allow the user to execute a range of standard queries on the database and then output the results to one or more files. These files could then be made available to the RP operator. Moreover, if the RP operator had access to the database, specialised queries could be created and executed. Either way, the DSS would enable the relevant information to be transferred from the design process to the RP process, resulting in better integration.

6.6 Conclusions

This chapter has defined the DSS by answering three questions: what design information is required to support RP?, what format should this information be in? and how will the information be used to make decisions about the use of RP? The system has been defined to satisfy the seven characteristics laid down by the specification described in Chapter 5. The result is a system design which requires the designer to identify all the design information pertinent to the application of RP, to attach this information to volumetric and surface features in a product model and to use software modules which access this information to help make key decisions about the use of RP. The DSS has been described in sufficient detail to enable its full implementation. However, the description is deliberately designed to be independent of any specific hardware or software. The next chapter addresses the partial implementation of the DSS.

CHAPTER SEVEN

IMPLEMENTATION AND EVALUATION OF THE DESIGN SUPPORT SYSTEM FOR RAPID PROTOTYPING

The previous chapter described the definition of the DSS which was created from the specification developed in Chapter 5. The central pillar of the definition was the use of a feature-based product model database. The next task was to implement the DSS for RP incorporating as many as possible of the modules defined in Chapter 6. The aim of this implementation was not to create a fully functional DSS but rather a "demonstration package" which would illustrate both how the feature-based product model could be used and the benefits it would yield.

7.1 Choice of Hardware and Software

An IBM compatible personal computer (PC) was chosen as the hardware platform for the DSS. This was because the author had permanent access to a PC and because it would allow the system to be more portable since PCs are abundant in both industry and academia.

The choice of software for implementing the system was made using several criteria:-

1. Ability to support product modelling
2. Availability within author's department
3. Level of use within industry

No single software package fully satisfied all the requirements dictated by these criteria. Rather, it was necessary to use a combination of two packages, Microsoft (MS)-Access [139] and AutoCAD [140]. MS-Access is a high level relational database management system (RDBMS) which facilitates the definition of the complex data structures required for product modelling. AutoCAD is a computer aided design (CAD) package which provides both a graphical user interface and a high level programming language for data manipulation. Both were readily available within the department and are in common use in industry.

7.2 Shared Database

The DSS defined in Chapter 6 envisaged a computerised system which would be based on a shared database approach. Therefore, the most critical part of the system implementation was to create a database with the correct structure to enable data to be readily shared by various software modules. The required data structure for the system had already been defined using EXPRESS-G as shown in Figure 6.3. This data structure was mapped into the MS-Access RDBMS with EXPRESS-G entities being represented by tables whose fields related to the entities' attributes. The EXPRESS-G hierarchical relationship of an entity being another entity's attribute (e.g. vector being an attribute of facet) was represented within MS-Access by having a field in the child table which contained a reference to the unique identifier in its parent table. In this way, a hierarchical structure was created. An example of mapping for the vector entity is shown in Figure 7.1. Similar mappings were used to create the other tables in the database. Some extra fields were added and the entities vol_feature and STL_file were combined since they had a one-to-one relationship. The database tables, their fields and the hierarchical links between them are shown in Figure 7.2.

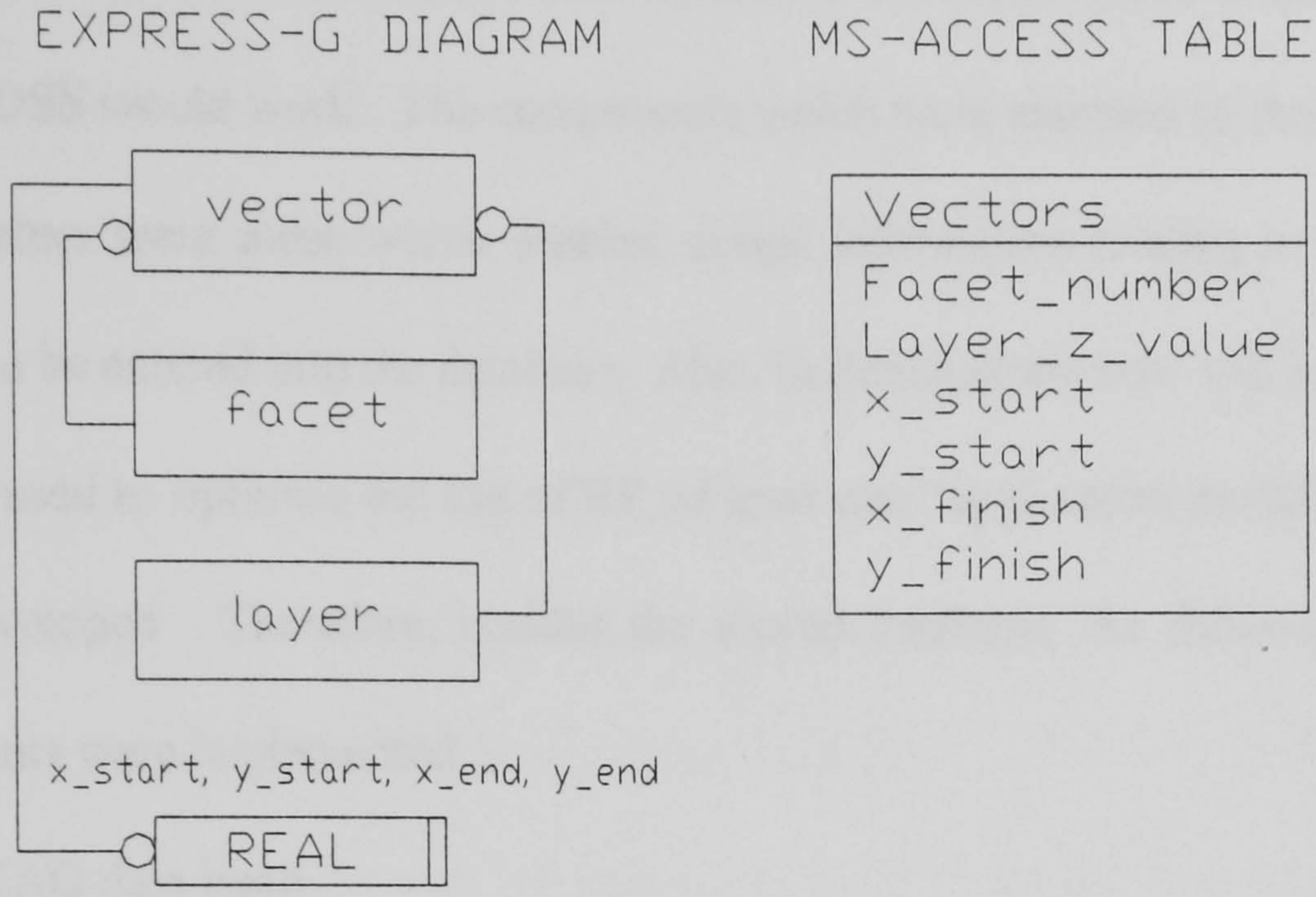


Figure 7.1 Mapping an EXPRESS-G entity into an MS-Access table.

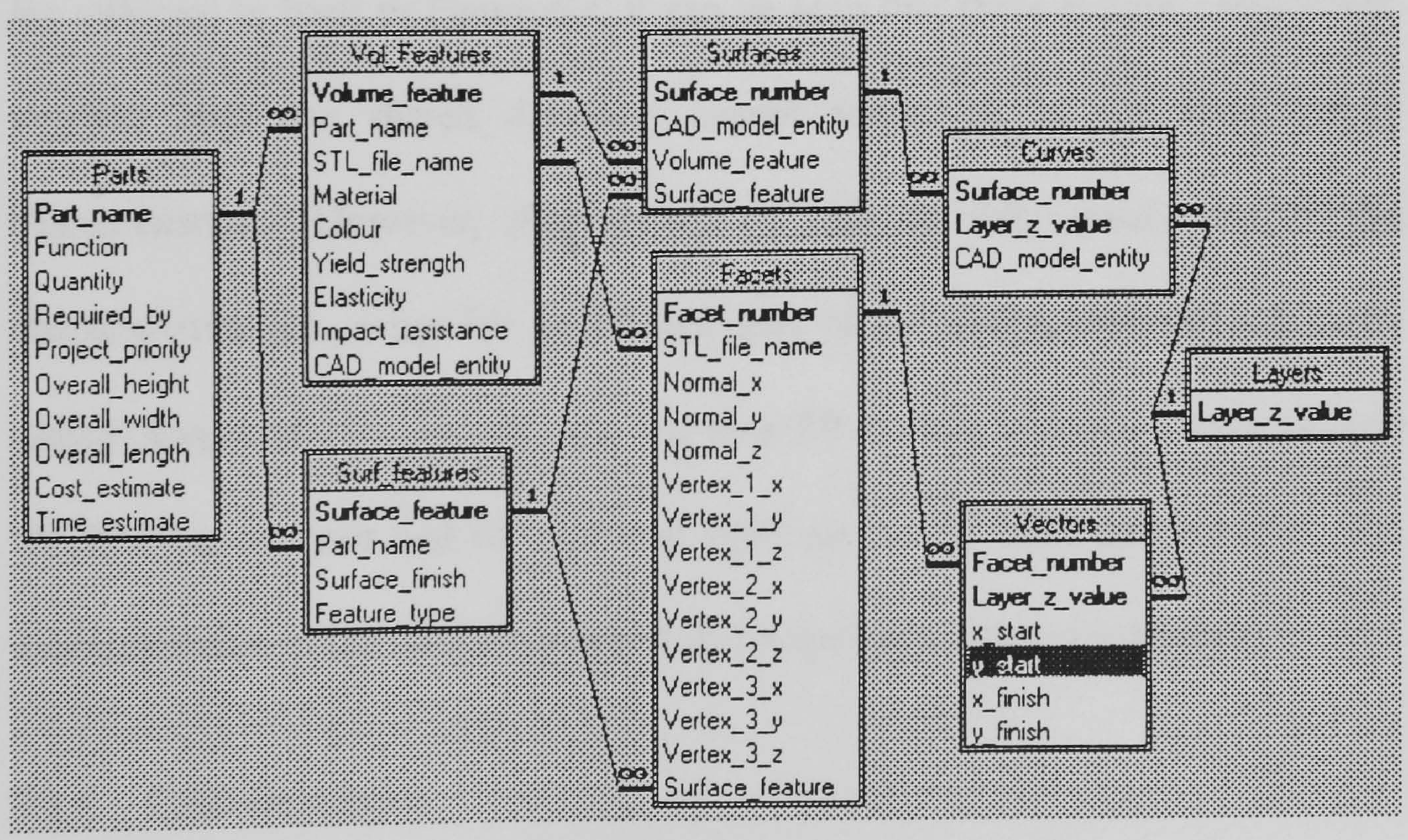


Figure 7.2 Structure of the shared database.

7.3 Other System Components

The full requirement for system components had already been defined as discussed in Chapter 6. However, not all of these needed to be implemented to demonstrate how the DSS would work. The components which were essential to the operation of the system were those which enabled design information relating to individual features to be entered into the database. Also, to demonstrate how this information could be used to optimise the use of RP, at least one "application module" needed to be developed. Therefore, besides the shared database, the following system components were implemented.:-

1. CAD data input
2. Feature editor
3. Surface finish optimisation

By referring to back to Figure 6.4, it can be seen that these system components, together with the shared database, cannot satisfy all of the ideal system characteristics. However, they should be able to fully satisfy one of the characteristics (i.e. make RP an integral part of the design process) and partly satisfy three others (i.e. ensure right first time RP models, improve communication between the designer and RP operator, optimise the RP build parameters). The implementation of the three chosen system components is described below.

7.3.1 CAD Data Input

The top-level information about individual components and their features must be entered into the DSS by the designer. To facilitate this, data-entry forms were created to input part data, volume feature data and surface feature data. These forms are shown in Appendix C. The data input via these forms serves two purposes. Firstly, it defines the features which belong to a particular component, and secondly, it allows non-geometric information to be entered against either the whole component or any of its features. Examples of this information are the number of parts required, the part's material(s) and its required surface finish(es).

Once the component and its features are defined, it is then possible to enter the geometry design data. To enable design data to be entered from a wide range of CAD systems and not just those supporting FBD or even B-Rep modelling, it was decided to use STL files to enter the geometry into the shared database. The STL files normally generated by CAD systems are in a binary format rather than the human-readable ASCII format which is also available. Therefore, a software module called "load_stl" was designed to parse through binary STL files and load the numeric values for each triangle into the "Facets" table. The name of the STL file from whence it originated was recorded against each facet in the table. This module was written using the Access Basic programming language which is incorporated into MS-Access. A program listing for this module is given in Appendix D.

7.3.2 Feature Editor

Volumetric features within a component were handled simply by using several STL files, one for each feature. This was represented within the "Volumetric_features" table using the field entitled "STL_file_name". This provided a link from the volumetric feature to each of its constituent facets. Surface features were more of a problem since STL files are designed to represent solid models only. It was decided that the best strategy to deal with this problem was to provide the user with a mechanism for identifying the constituent facets of each surface feature. This needed to be done using a graphical interface since the facets making up each feature shape could only be identified if they could be seen by the user. There are no graphical interface functions provided within MS-Access and so it was necessary to use a different package. This is where AutoCAD came into play since it has a programming language (AutoLISP) that enables direct manipulation of the graphics entities shown in the CAD drawing.

To enable the individual facets in each surface feature to be identified, it was necessary to go through a three stage procedure as follows:-

Stage 1. Load all facets representing a component into AutoCAD.

Stage 2. Identify and list the facets contained within each surface feature.

Stage 3. Create a link in the MS-Access database between each surface feature and all facets which belong to it.

A separate software module was created to perform the tasks in each of these three stages.

Firstly, the facets representing the component needed to be loaded into the AutoCAD system. It would have been possible to do this by loading the STL files directly into AutoCAD. However, if this was done, the facets would not have had any link to those stored in the MS-Access database. Therefore an alternative approach was used. The "load_stl" module described above was modified so that in addition to inputting facets into the MS-Access database, it also output the facet co-ordinates, together within their unique identifying numbers, to a neutral file. An example of such a neutral file is given in Appendix I. This neutral file was then ready for loading into the AutoCAD system. An AutoLISP program called "facetsin" was written to load the neutral file into AutoCAD and to display each facet as a triangle with its unique identifying number shown it the centre of the triangle. The program listing for this module is shown in Appendix E and an example of the display seen in AutoCAD is shown in Figure 7.3.

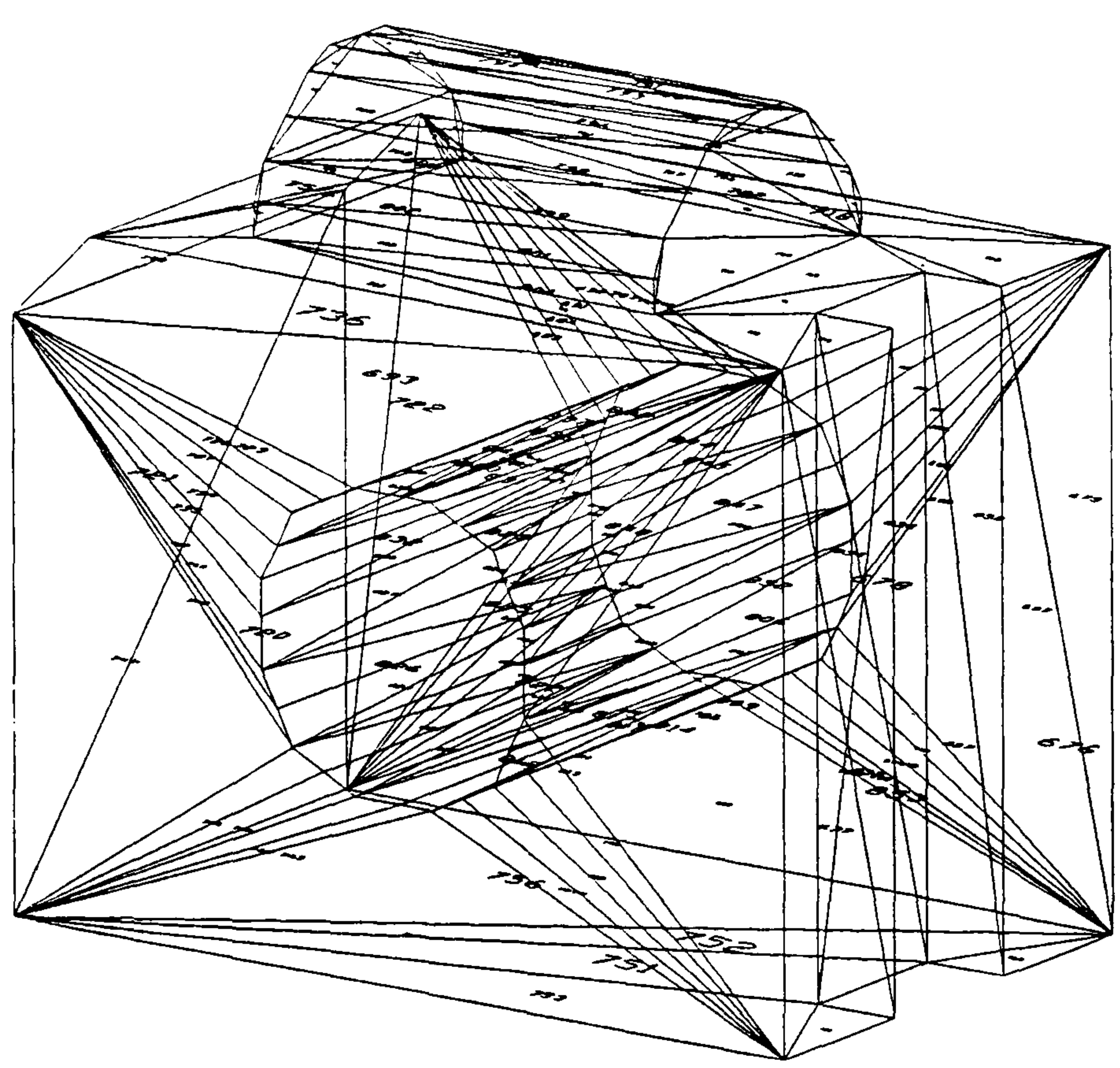


Figure 7.3 Example of the facets display seen in AutoCAD.

Secondly, the facets in each surface feature needed to be identified and listed. A second AutoLISP program, called "selfacet" was written which enables the user to digitise the numbers of all the required facets on the CAD screen (either individually or in groups). The program then writes all these unique identifying numbers into an ASCII text file which is named by the user. One such file must be created for each surface feature in the component and the file names should reflect the features they belong to. The program listing for "selfacet" is shown in Appendix F.

Thirdly, the link in the MS-Access database between each surface feature and all the facets belonging to it had to be established. This was done using another Access Basic module which reads in a facet list file and then, for all the facet numbers listed, inserts the file name against the "surface_feature_name" field in the "Facets" table. The module is called "assign_facets" and the program listing is shown in Appendix G. Finally, the name of the facets list file is entered into the "file_name" field in the "Surface_features" table. This creates the link between the individual facets and the surface feature they belong to. A diagram showing the relationship between the different feature editing modules and the exchange files used to transfer data between them is shown in Figure 7.4.

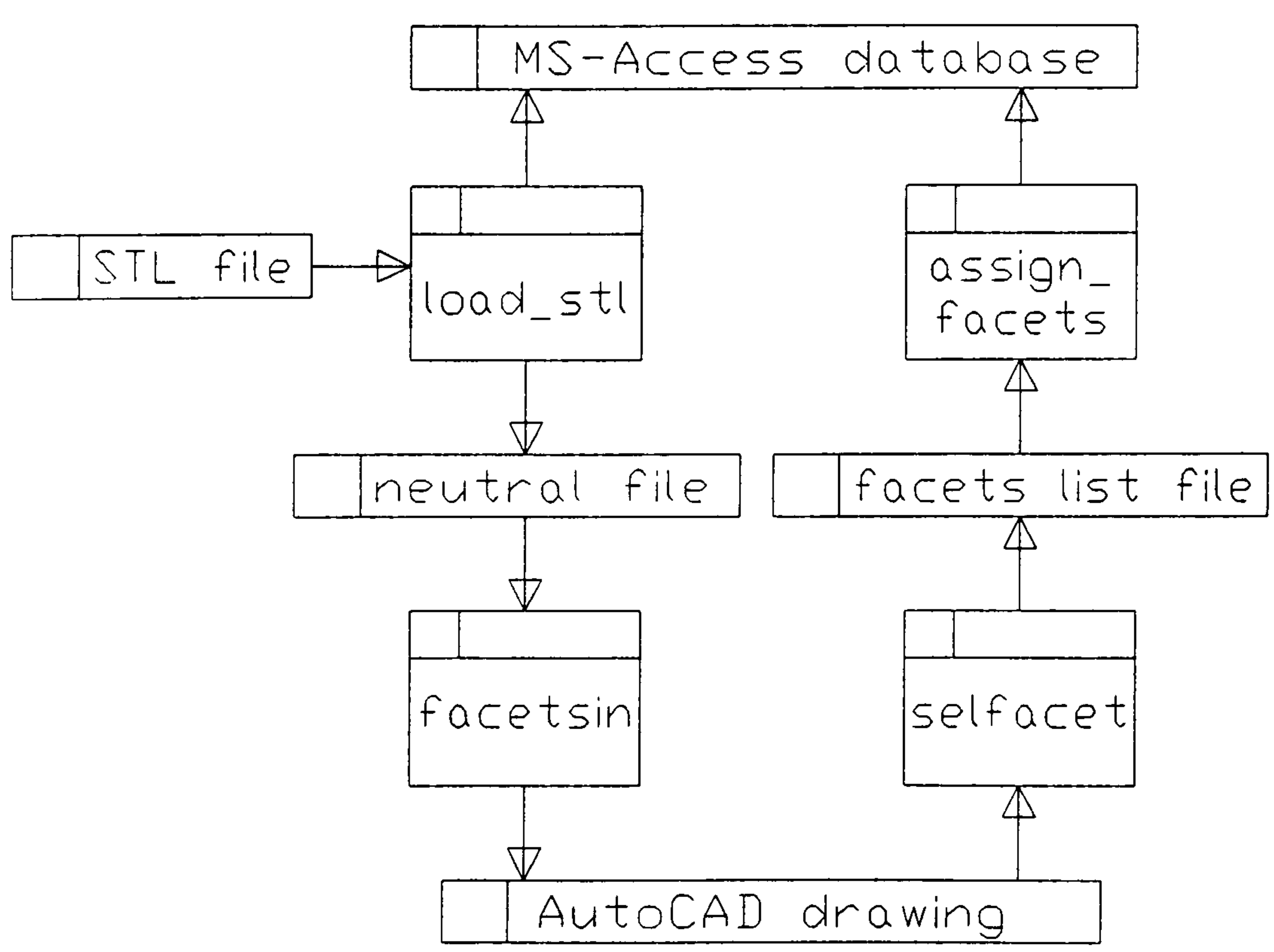


Figure 7.4 Relationship between different feature editing modules.

7.3.3 Surface Finish Optimisation

The application chosen to illustrate the benefits of using the system was that of calculating optimum stereolithography model orientation to achieve required surface finish values. This application was selected because it relies heavily upon non-geometric design information, i.e. surface finish, and because much work has been done within the author's department on the relationship between model orientation and surface finish [138, 141, 142, 143, 144, 145]. Also, the ability to optimise part orientation to achieve required surface finish is an essential part of using RP models for tooling applications. Therefore, this application will be of real value to the multitude of RP users working in this area.

The definition of surface finish (also called surface roughness) used for this work was the arithmetic mean value (Ra) which is based on the schematic illustration of a cross-section through a rough surface shown in Figure 7.5. The centreline shown is located so that the area above the line is equal to the area below. A number of measurements are taken from the centreline perpendicularly to the surface. The arithmetic mean value for surface finish is then given by the following equation:-

$$Ra = (a + b + c + ...) / n$$

where a, b, c, etc. are absolute values and where n is the number of measurements.

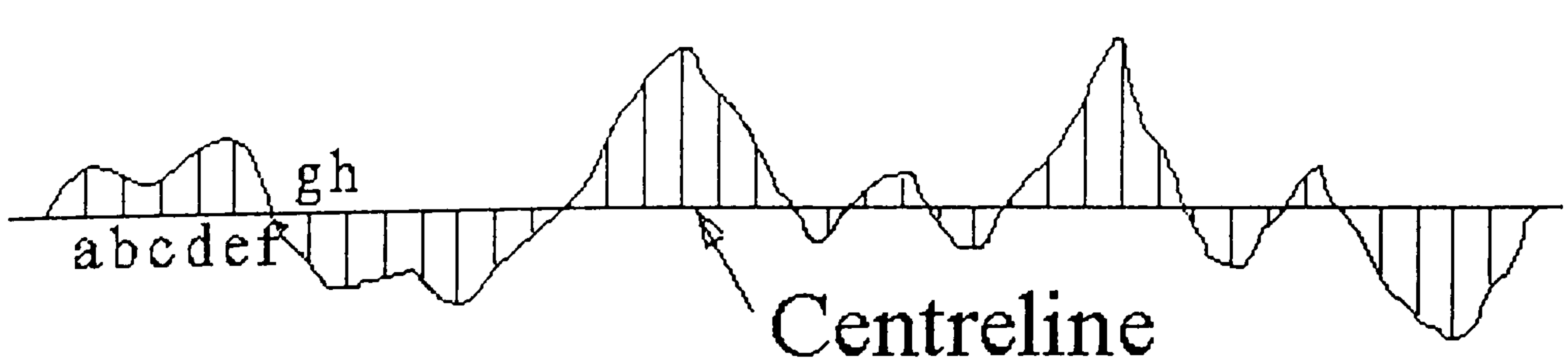


Figure 7.5 Schematic diagram used to define surface finish [26].

A software module called "calc_surf_fin" was written in Access Basic for this application. The principle behind the software module was that surface finish for the faces on a stereolithography model is highly dependent upon the normal vector of each face. The actual surface finish which can be achieved has been mathematically predicted and experimentally verified by Reeves [138]. The relationship between normal vector angle to the horizontal and surface finish for a particular set of stereolithography build parameters is shown in Figure 7.6.

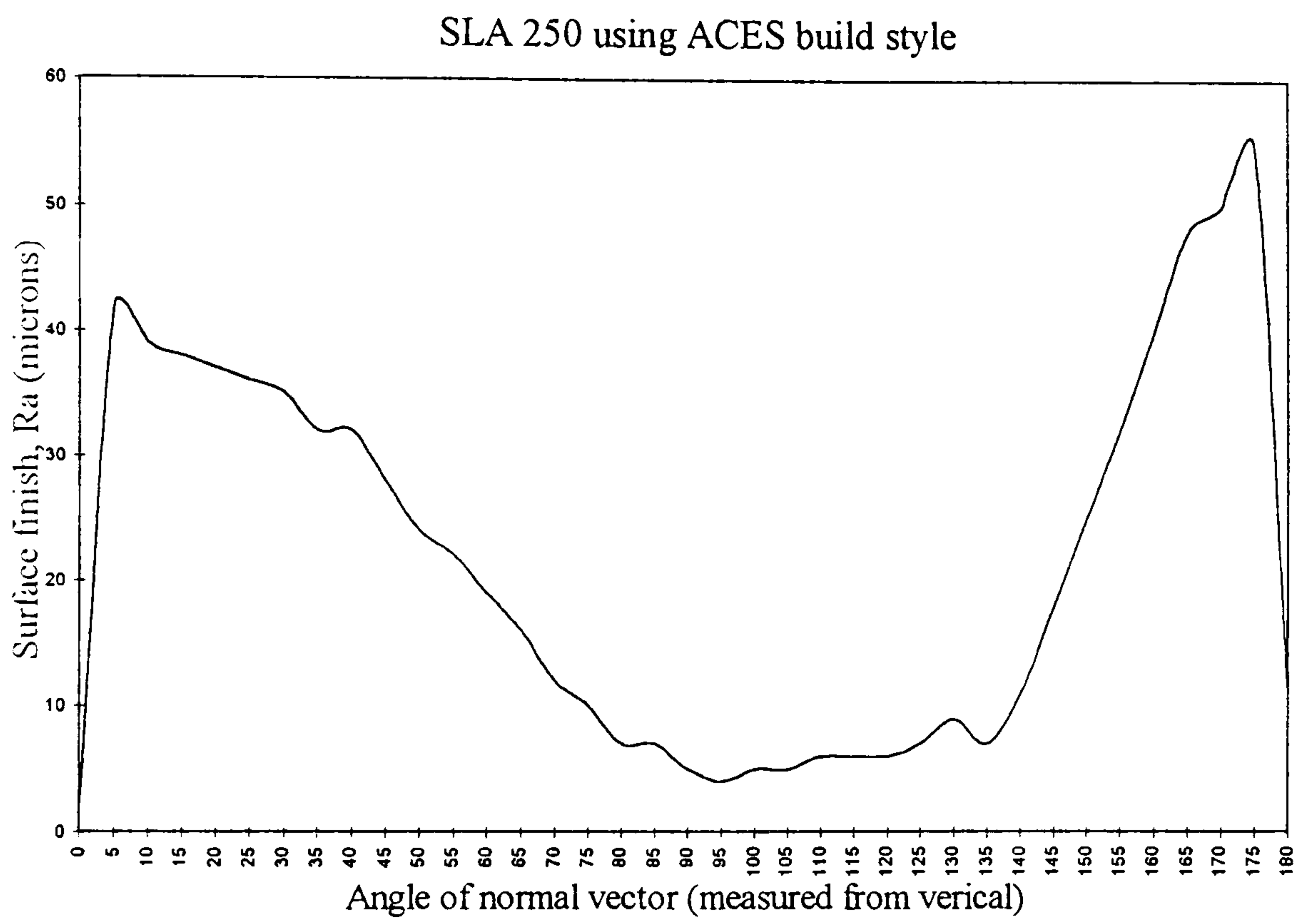


Figure 7.6 Relationship between normal vector angle and surface finish [138].

Once the normal vector for each face is known, the surface finish for that face can be predicted. The method for achieving this is described below.

Assuming that the stereolithography model is being built from an STL file, the original normal vectors for each facet are readily available. The normal vector for each facet will have three orthogonal components, Vx, Vy and Vz. If the model is re-orientated before being built, these component vectors will also be re-oriented. Assuming that the model is first re-oriented by a rotation around the X axis through an angle Ax, the effect upon the component vectors, Vx, Vy and Vz, is seen in Figure 7.7. Following the rotation, the newly positioned component vectors are once again resolved into the X, Y and Z directions, resulting in the following equations:-

$$Vx' = Vx$$

$$Vy' = (Vy * \cos(Ax)) - (Vz * \sin(Ax))$$

$$Vz' = (Vz * \cos(Ax)) + (Vy * \sin(Ax))$$

(note that the Vx component vector is unchanged by a rotation around the X axis)

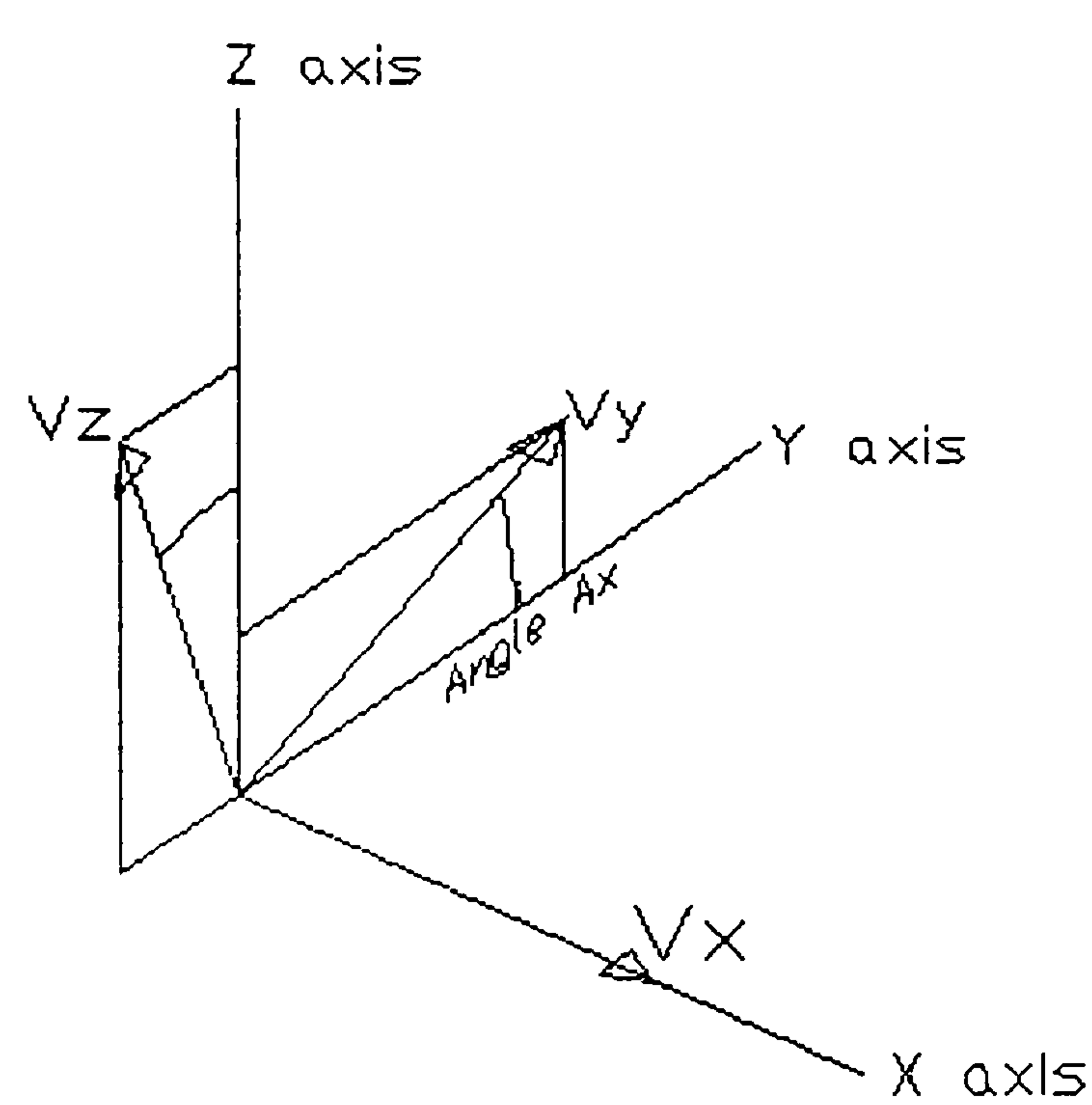


Figure 7.7 Effect of rotation around X axis upon Vx, Vy and Vz.

If the model is now re-oriented by a second rotation this time around the Y axis through an angle Ay, the effect of this rotation upon the new component vectors

Vx`, Vy`, and Vz` is seen in Figure 7.8. Once again, the newly positioned component vectors are resolved into the X, Y and Z directions, resulting in the following equations:-

Vx`` = (Vx` * cos (Ay)) + (Vz` * sin (Ay))

Vy`` = Vy`

Vz`` = (Vz * cos (Ay)) - (Vx * sin (Ay))

(note that this time, the Vy` component vector is unchanged by a rotation around the Y axis)

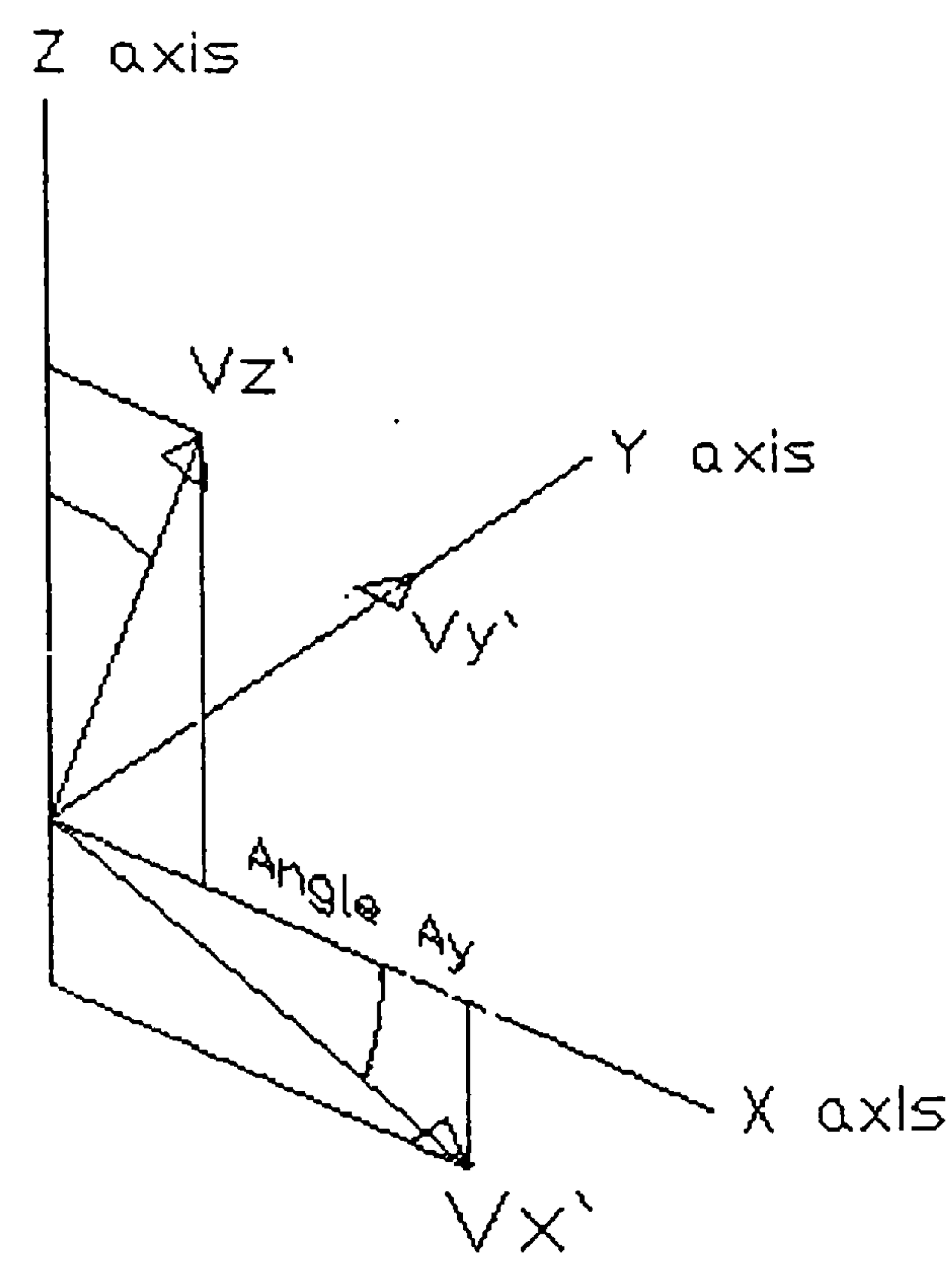


Figure 7.8 Effect of rotation around Y axis upon Vx`, Vy` and Vz`.

The values of Vx`, Vy` and Vz` can now be taken from the first set of equations and substituted into the second set to give the following equations:-

Vx`` = (Vx * cos(Ay)) + (((Vz * cos(Ax)) + (Vy * sin(Ax))) * sin(Ay))

Vy`` = (Vy * cos(Ax)) - (Vz * sin(Ax))

Vz`` = (((Vz * cos(Ax)) + (Vy * sin(Ax))) * cos(Ay)) - (Vx * sin(Ay)) where Vx, Vy and Vz are the orthogonal components of the original facet normal vector and Ax and Ay are the angles of rotation around the X and Y axes (rotation around X axis is followed by rotation around Y axis). Vx``, Vy`` and Vz`` are the three orthogonal components of the re-oriented facet normal vector.

Thus, for any given re-orientation, the new normal vectors and hence surface finish for each facet can be obtained (using values taken from the graph in Figure 7.6).

The operation of the "calc_surf_fin" software module is illustrated by the flow diagram in Figure 7.9. Within the MS-Access database, groups of facets will have been assigned to surface features for which the designer can input a surface finish requirement. The software program loops through all the possible build orientations (at 5° intervals) and, for each facet, calculates the ratio between the achievable surface finish with the required surface finish. For each orientation, the program checks to see if there are any facets for which the ratio is greater than one. These orientations are labelled as having a problem. The user can then select an orientation from the remaining problem-free alternatives. If none of the orientations are problem-free the user would normally select the one that comes closest to a solution. To this end, the program also calculates the average ratio for each orientation and indicates the orientation which has the lowest overall average. The average ratio is weighted to take account of the differing surface areas of all the facets. For each orientation, the program also outputs to the file the number of the facet with the worst surface finish ratio and the value of this ratio. A program listing for this module is shown in Appendix H.

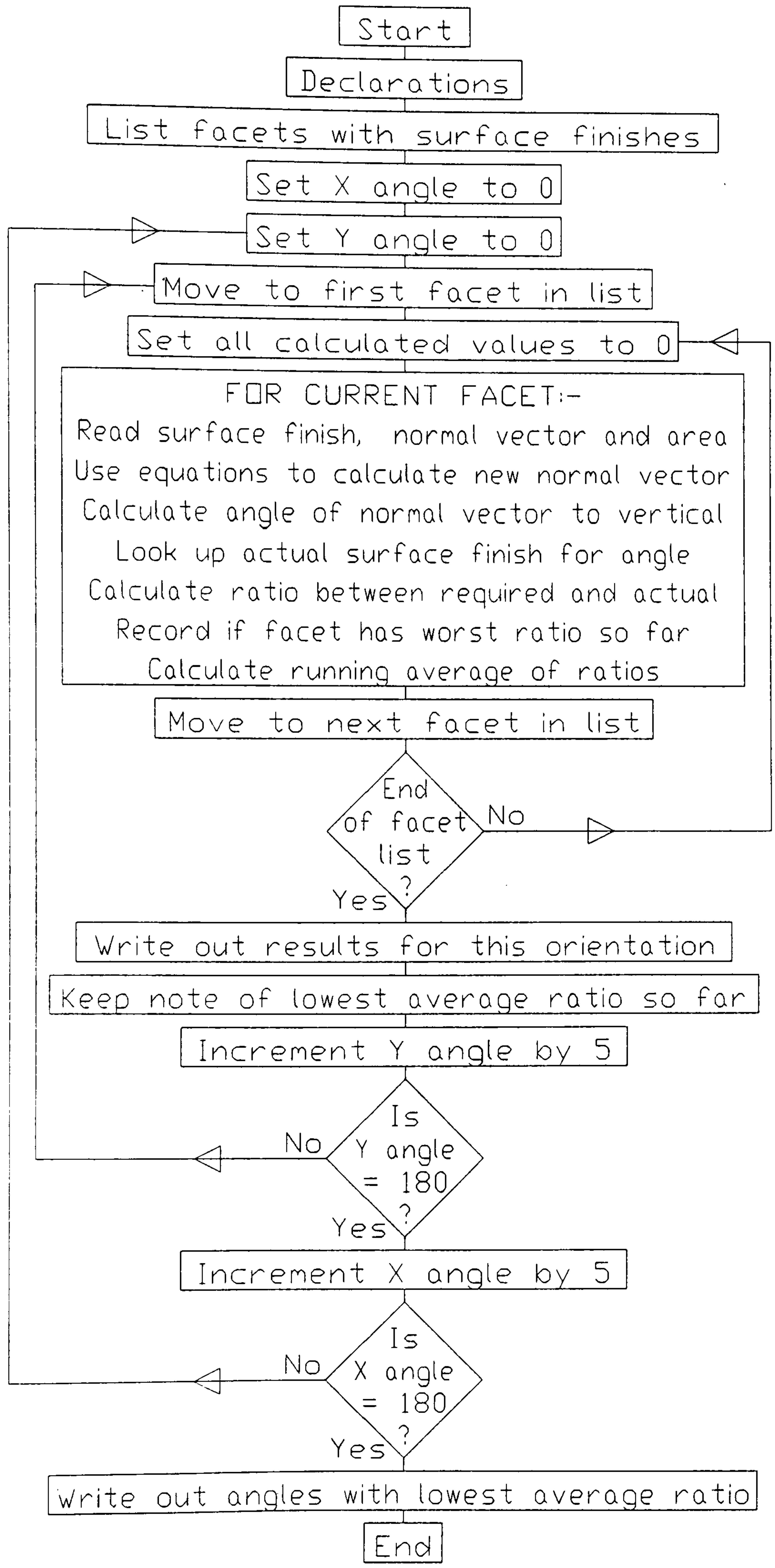


Figure 7.9 Flow diagram of the "calc_surf_fin" software module.

7.4 Using the System

To give the reader a better understanding of how the DSS system works, the application of the system to a particular component design is now described. The component selected for this purpose was a simple test piece originally designed to illustrate the use of features within a CAD model. The component is shown in Figure 7.10. This was thought to be an ideal demonstration part since it has several different form features, each of which can be assigned different surface finishes. The fact that the features have varying orientations as well as different surface finish requirements makes it difficult to estimate what the optimum build orientation would be. This component will demonstrate how the feature-based approach of the DSS is able to optimise the RP build orientation to achieve the required surface finishes. The following sections give a step-by-step guide to using the various modules within the system.

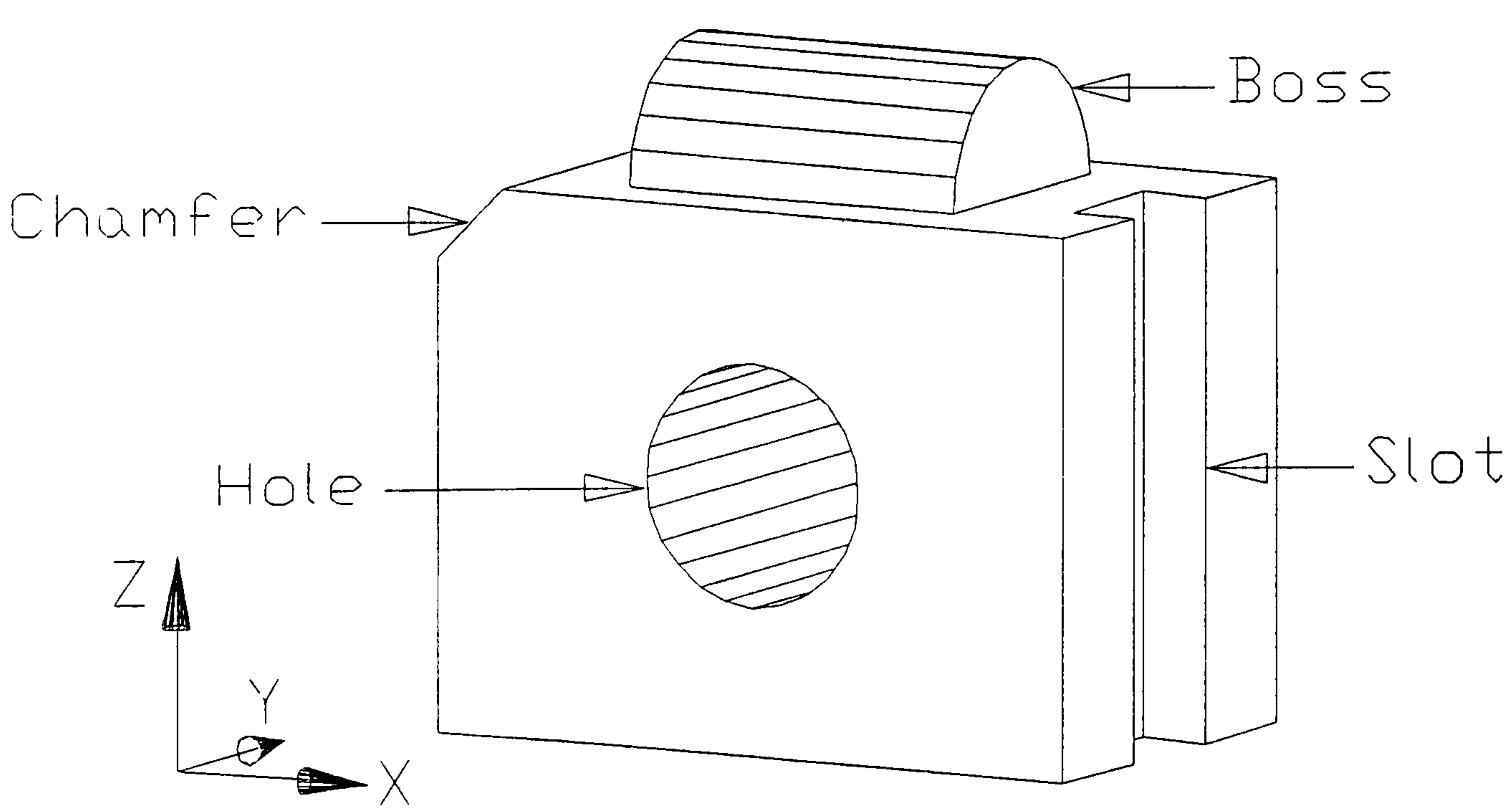


Figure 7.10 Component selected to demonstrate using the DSS.

7.4.1 Starting Procedures

Before the user starts to use the system, certain facts must be determined and noted. The first of these is the name or identifying number of the component being considered. This will be used to uniquely identify the component within the MS-Access database. Secondly, the user must have an understanding of what features there are within the component. These may be volumetric features, surface features or a combination of both. If the user is the designer who created the component this should be no problem. However, if this is not the case, then liaison with the designer will be necessary. This will avoid the pitfalls of an "over-the-wall" approach to using RP and the lack of communication this can cause. In the case of a component that has several volumetric features, e.g. for different material colours, a single STL file must be available for each feature. This is best achieved within the designer's CAD system where the component can be split into several solid models and an STL file created for each one. Finally, unique names must be assigned to all the features in the part, again for identification purposes in the database.

7.4.2 Initiating Software Packages

The user must have access to a PC which has MS Windows, MS-Access and AutoCAD for Windows loaded onto it. The user must enter the Windows environment, start AutoCAD and start MS-Access. Within AutoCAD, the AutoLISP files needed to run the DSS system must be loaded, if this has not already been done during start-up. This is achieved by clicking on the "Load Applications" option of the "File" menu, highlighting the facetsin.lsp and selfacet.lsp files in the list of applications provided and then clicking on "Load". The AutoCAD window should then be minimised. Within MS-Access, the database containing the DSS must be opened. This is done by clicking on the "Open Database" option of the "File" menu, entering the name of the .mdb file used for the database and clicking on "OK". MS Access then opens a window which shows the different types of objects within the database, e.g. tables, forms, queries, modules, etc. Clicking on any one of these object types will cause all objects of this type to be listed in the window.

7.4.3 Entering Part Data

To assign attributes at the top level of the database structure, i.e. whole component attributes, the user must click the "Forms" object button in the database window. This is followed by a double-click on the "Part_data_input" list item. The form for entering part data is then opened and the user can enter text and values in each of the slots. Only one of the slots must be completed, i.e. "Part_name", the others being optional (some slots have default values). At least one part must exist in the database before any feature attributes can be assigned. The demonstration part is called "features" and requires the attributes function, quantity, overall_length, overall_width and overall_height to be set to "demonstration", 1, 50, 30 and 47.5, respectively.

7.4.4 Entering Feature Data

To assign attributes at the next level of the database structure, i.e. feature attributes, the user must have previously clicked the "Forms" object button in the database window. There is then a choice of double-clicking on either

"Volume_feature_input" or "Surface_feature_input". Each part must contain at least one volumetric feature before any STL data can be entered and so for a new part, volumetric feature data would normally be entered first. When the form for entering volumetric feature data has been opened, the user can enter text and values in each of the slots. Again, some of the slots must be completed, i.e. "Volume_feature" and "Part_name". If the name of the STL file which contains the geometry of the feature is already known, it can also be entered at this stage. If the part is to have only one volumetric feature then obviously this feature must represent the whole of the part's volume and should be given a name to indicate this fact. If more than one volumetric feature is defined, each one should have a meaningful name perhaps related to its shape or function. The demonstration part has only one volume feature and this will be named "features_whole". The other attributes to be entered at this stage are part_name (features), STL_file_name (c:\acadwin\features.stl) and material (SL 5180). This material has been selected because it is one of the standard resins used with the Stereolithography ACES build style.

Although surface features are optional within the system, most of the envisaged applications (and certainly the implemented one) make use of them. Entering surface feature attributes is very similar to the process described for volumetric features. The form used is called "Surface_feature_input" and the compulsory slots are "Surface_feature" and "Part_name". As with volumetric features, the "Part_name" slots creates a hierarchical link with the part to which the feature belongs. It is at this level that attributes such as surface finish are entered. The surface features within the demonstration part are "boss", "hole", "slot" and "chamfer". Each of these is entered in turn with its required surface finish. The four features are arbitrarily assigned surface finishes of 25, 30, 35 and 40 microns respectively.

7.4.5 Reading in STL File(s)

Up to this stage, only non-geometric information about a part and its features has been entered. It may be possible that some future applications will use this information only. However, for the orientation application which has been implemented, it is also necessary to enter the shape of the part. This is done by reading in one STL file for each volumetric feature in the part. To do this, the user must open the database form entitled "convert_STL". Two slots need to completed, "STL_file_name" and "output_file_name". The user then clicks on the "Run Macro" button which executes the "load_stl" module described in Section 7.3.1. The result of this is that all the facets in the STL file are loaded into the database and also listed in a neutral file format. The user can now select another STL file and repeat the process. The names of all neutral files that are created should be noted by the user. The only STL file to be converted for this part is "c:\acadwin\features.stl" and the neutral file will be given the name "c:\acadwin\features.neu".

7.4.6 Assigning Facets to Surface Features

This is the most complicated part of using the system, made so by the need to work in both MS-Access and AutoCAD. However, providing the user follows the correct procedure, no difficulties should be encountered. Firstly, the MS-Access window should be minimised and the AutoCAD window opened. Then, in order to visualise the facets which define the geometry of the component, the command "facetsin" should be typed. This will simply ask the user for the name of the neutral facets file to be loaded. Upon hitting return, the facets will appear on the drawing window as triangular strings with a text number in the centre of each triangle. Execution of this command is repeated for each neutral file until the geometry of the entire component is visible. For the demonstration component, the resultant AutoCAD screen will be similar to that shown in Figure 7.3.

Secondly, still within AutoCAD, the "selfacet" command must be typed. This will ask the user for the name of the surface feature file to be created followed by a requirement to select all facets that belong to this feature. This can be done by clicking on individual facets or by using a window. To aid this process, the user can change viewing direction, zoom in and erase unwanted geometry. The "selfacet" command is repeated for every surface feature within the component, in this case, four. The result is a series of text files containing a list of facet numbers. The user must note the name of each facets list file. The files for the demonstration component will be called "boss.flf", "hole.flf", "slot.flf" and "chamfer.flf". The AutoCAD window can now be closed.

Finally, the MS-Access window must be maximised and the form called "assign_facets" clicked open. Once again, two slots must be completed, "surface_feature_name" and "input_file". The first slot contains a pull-down menu showing the surface features which have been previously defined during the step described in Section 7.4.4. Once the user has selected the desired feature, the name of the associated facets list file created in AutoCAD must be entered in the second slot. The user then clicks on the "Run Macro" button which executes the "assign_facets" module described in Section 7.3.2. The result of this is that, within the "facets" table of the database, all the facets listed in the input file have the name of their surface feature entered into the "surface_feature" field. The user can then select another surface feature and repeat the process. This process will be repeated four times for the demonstration part, once for each feature.

7.4.7 Running the Surface Finish Calculation Procedure

The steps described above will have resulted in the geometry of the component having been entered into the database in the form of volumetric and surface features with associated non-geometric information. The next stage is to use this design information to optimise a particular aspect of the RP process, i.e. model orientation in regard to surface finish requirements. This is done by clicking open the "calc_surf_fin" form within MS-Access, completing the two slots "Part_name" and "output_file" and clicking on the "Run Macro" button. This executes the "calc_surf_fin" module described in Section 7.3.3, resulting in the creation of a file which, for almost 1,300 different orientations, lists the average surface finish ratio, the x and y rotation angles, the facet at which worst surface finish ratio occurs and the worst surface finish ratio together with the optimum orientation angles (in terms of achieving the lowest average ratio). An example of an output file is given in Appendix J. The optimum orientation angles are also displayed in the "calc_surf_fin" form.

When the orientation optimisation module was run using the demonstration part, two orientations were found which satisfied the surface finish requirements for all four features. These were with an X angle rotation of 55° and a Y angle rotation of 150°, or an X angle rotation of 125° and a Y angle rotation of 30°. The first of these orientations is shown in Figure 7.11. The two orientations gave identical surface finish values as they were actually mirror images of one another. This was to be expected since the part is symmetrical. The average surface finish ratio across the whole part was 0.408 showing that for most of the part, surface finish was well within requirements. This is not an obvious solution and would probably not have been selected intuitively by an experienced RP operator.

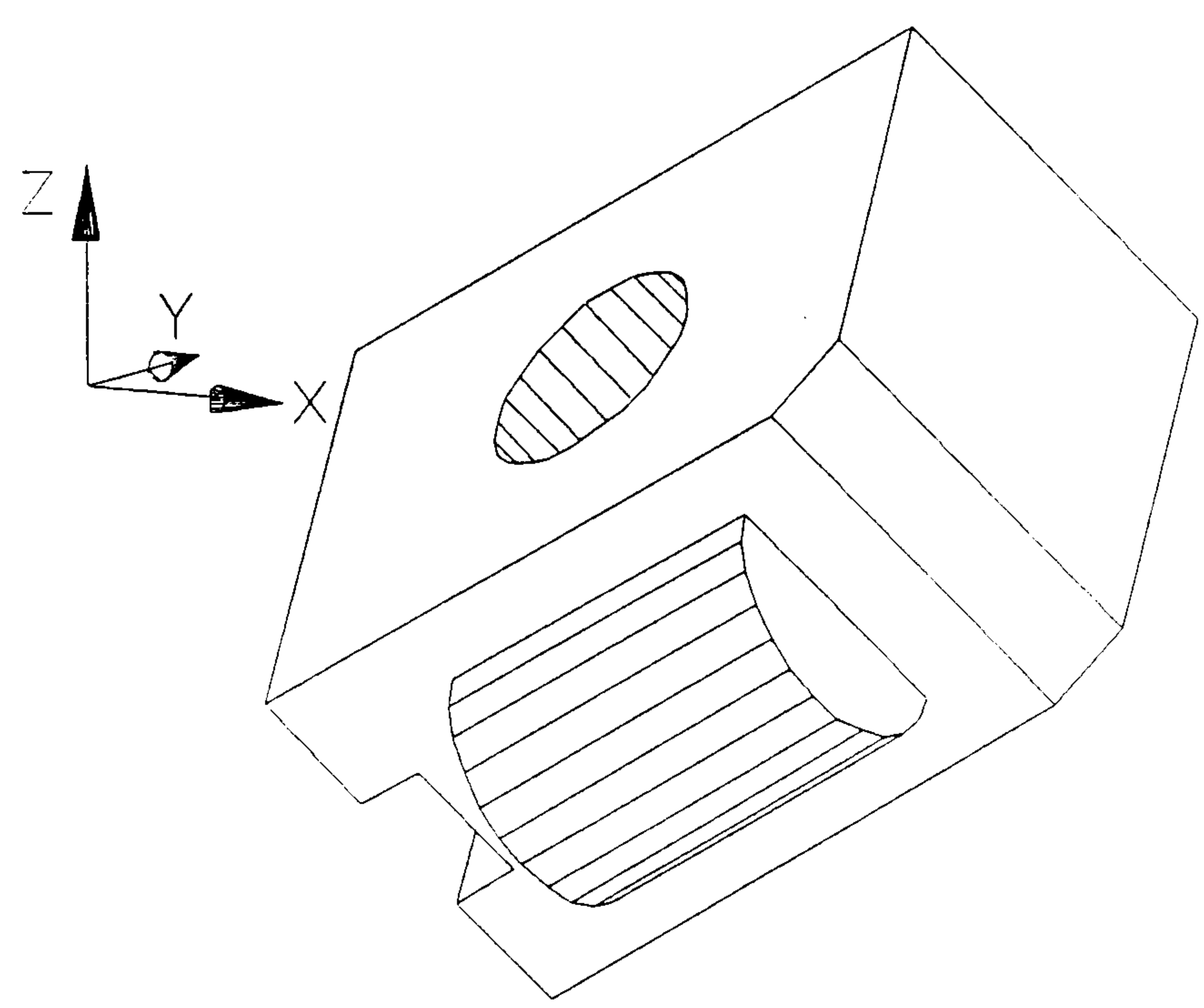


Figure 7.11 Optimum orientation of demonstration part.

The orientation optimisation algorithm used in the DSS system has a single objective, i.e. to achieve an acceptable surface finish on all the features where a value has been specified by the designer. There are other criteria which orientation optimisation could take into account, e.g. the build time for the part, the requirement for support structures, the stability of the part during the build process, the number of layers required, the build height for the part, the avoidance of trapped volumes and part accuracy. Some of these are inter-related, e.g. number of layers and build time. Others are applicable to only some RP techniques, e.g. requirement for support structures (some RP techniques require no additional supports). There may also be a conflict between two or more of the criteria, e.g. building the part with a low overall height may not be compatible with good accuracy. Therefore, if the orientation optimisation algorithm was to be expanded to be multi-objective in nature, it would be necessary to incorporate some method of achieving an acceptable compromise between the different criteria. One method of doing this is to give weighting factors to each criteria which can be altered by the user. These would be used to calculate an overall score for the orientation based on how well each criteria is met and the weighting it has. An example of the type of multi-objective orientation optimisation program which could be used is described by Cheng et al [98].

The optimisation orientation has only been applied to one RP technique, i.e. stereolithography. It could equally-well be used for any RP technique where surface finish is mainly dependent upon surface orientation. This is the case for most RP techniques which are based on distinct layers, the "stair-stepping" between layers being the greatest source of poor surface finish. The fact that the optimisation algorithm does not consider support structures actually makes it more suitable for RP techniques such as laminated object manufacture and solid ground curing which provide inherent support for the model during the build process.

Likewise, the fact that neither the model height nor number of layers used are considered makes the orientation algorithm more suitable for RP techniques where build time is highly dependent on model volume and much less so on the delay time between layers. An example of this is 3D welding where there is very little inter-layer delay time. Therefore, the build time does not vary nearly so much with orientation as it does for stereolithography. The only reason why stereolithography was chosen was the readily available data on surface finish versus surface orientation.

7.4.8 Sensitivity Analysis

The demonstration part was now subjected to a two-way sensitivity analysis. Firstly, to see how much a change in orientation would alter the achievable surface finish, and secondly, to see how much a change in surface finish requirement would alter the results of the orientation optimisation. The first part of the sensitivity analysis would allow the designer to see what level of flexibility there would be in using orientation angles different from the recommended ones. This might be desirable to help cater for other orientation criteria as discussed in the previous sub-section.

The results form the orientation optimisation were imported into a spreadsheet package and used to plot three dimensional graphs of surface finish ratio against X and Y orientation angles. This was done for both the average surface finish ratio for the whole part (see Figure 7.12) and for the worst surface finish for any facet in the part (see Figure 7.13). By looking at these plots the designer can quickly

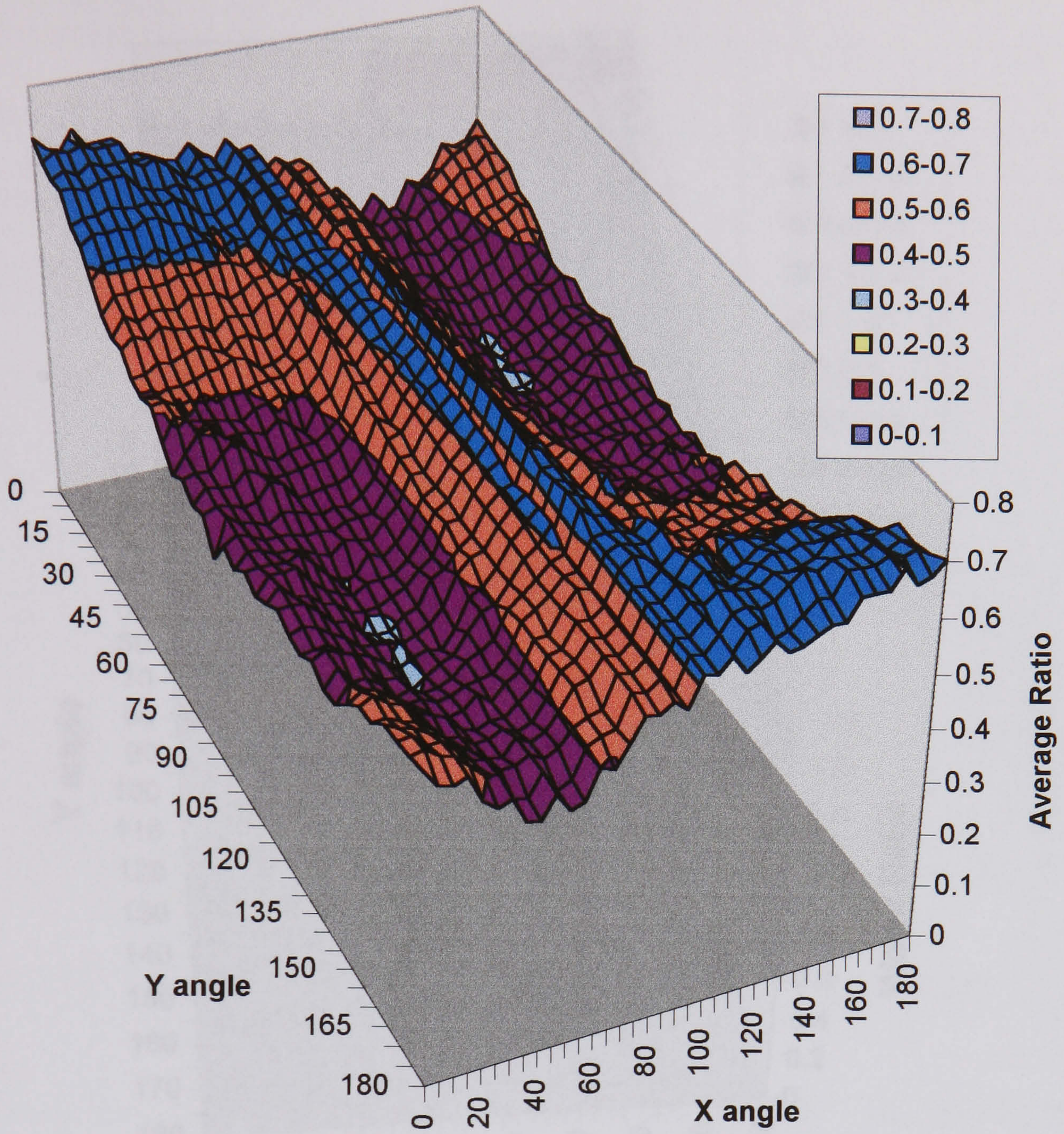


Figure 7.12 Result of sensitivity analysis for average surface finish ratio.

obtain a qualitative indication of what effect a change in X or Y angle will have upon the surface finish ratios. For average surface finish, changing the Y angle has a much smaller effect than changing the X angle, as indicated by the elongated shape of the two minimum regions shown in light blue in Figure 7.12. For the worst surface finish ratio, the picture is more complicated as the minimum regions shown in orange-brown in Figure 7.13 are actually "kidney-shaped". However, it would seem that for this variable, there is more sensitivity to the Y angle than the X angle.

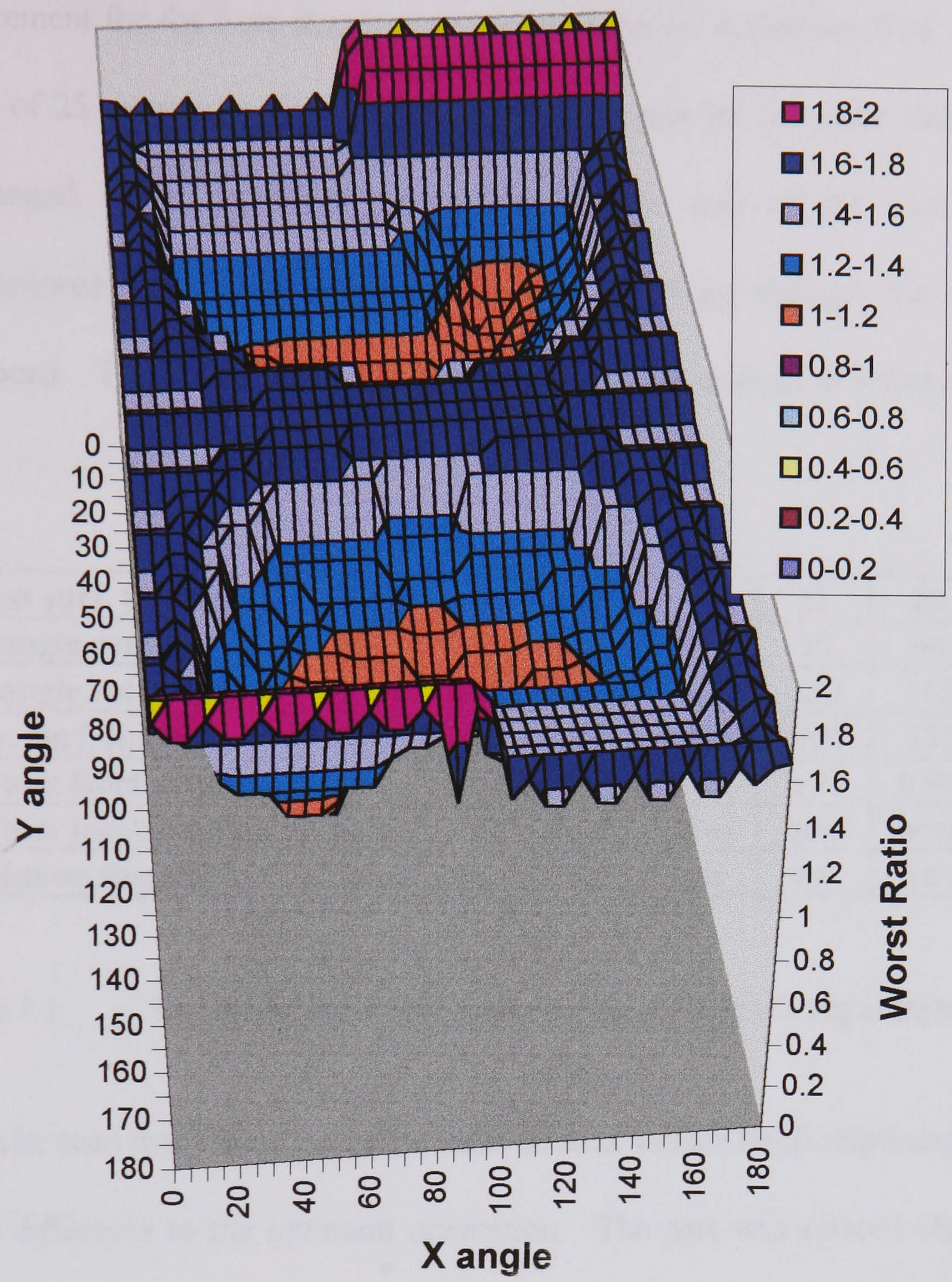


Figure 7.13 Result of sensitivity analysis for worst surface finish ratio.

The second part of the sensitivity analysis allows the designer to see what effect a relaxation (or tightening) of the specified surface finish requirements would have upon the orientation results. This would be useful if the initial results showed that the required surface finish could not be achieved for a critical part feature. It could be determined if relaxing the requirement for another feature would rectify this problem. As an example, the surface finish requirement for the boss feature was varied up to +/- 6 microns from its current value of 25 microns, whilst leaving the requirements for the other three features unchanged. The optimum orientation (actually one of the two optimum orientations) was identified in each case by searching through the output file produced. The results obtained form this sensitivity analysis are shown in Table 7.1.

Boss surf. fin. req't	**19**	**21**	**23**	**25**	**27**	**29**	**31**
X angle rotation	45	45	45	55	55	60	60
Y angle rotation	145	145	145	150	150	145	145
Av. surf. fin. ratio	.407	.397	.388	.408	.400	.375	.370
Worst facet ratio	1.07	1.07	1.07	0.96	0.93	0.96	0.93
Worst facet location	hole	hole	hole	boss	hole	boss	hole
Solution found?	no	no	no	yes	yes	yes	yes

Table 7.1 Results of sensitivity analysis on surface finish requirements.

It can be seen that a decrease in the value of boss surface finish requirement made a small difference to the optimum orientation. The part was rotated slightly in an attempt to meet the tighter requirement. This caused the worst surface finish ratio to be on a hole facet rather than a boss facet (this was determined by searching for the worst facet number in the "facets" table to see what feature it was assigned to). However, even with this slight rotation, the tighter requirement could not be met. The average surface finish ratio at first improved due to this rotation but then began to worsen in line with the tightening requirement specified for the boss. When the surface finish requirement for the boss was progressively relaxed, the part was rotated in the opposite manner in an attempt to improve the surface finish of the hole feature which had the second most demanding requirement of 30 microns. As a result of this, and due to the relaxed requirement for the boss, the average surface finish ratio improved.

The two-way sensitivity analysis showed that the relationship between orientation, average surface finish ratio and worst surface finish ratio is very complex and therefore difficult to predict without the aid of a computer program. When it is not possible to achieve the surface finish requirements for all the features in a part, there is a trade-off to be reached between achieving the best overall average surface finish for the whole part or the best possible surface finish ratio for any particular feature. This trade-off could perhaps be automated by assigning different priorities to different features which would be incorporated into the surface finish calculation.

7.4.9 Finishing Procedure

Once the user has finished using the system, MS-Access and AutoCAD can both be exited by clicking on the "Exit" option of their "File" menus.

7.5 Evaluation of the System

Once the DSS for RP had been implemented and used, it was necessary to evaluate its performance compared to the ideal system characteristics listed in Chapter 5. As stated in section 7.3, the system components which have been implemented will only contribute towards four of the characteristics. Therefore, the evaluation was restricted to these four. The result of the evaluation against each characteristic is presented below.

7.5.1 Make RP an Integral Part of the Design Process

The current method most often used for creating an RP model from a CAD model is for the STL file to be created by the designer and sent to the RP operator. The STL file may sometimes be accompanied with other written or verbal instructions. This is an "over-the-wall" approach and leads to RP being used as a "bolt-on option" rather than an integrated design tool. The implementation of the DSS for RP allows the designer to take the STL file and combine it with other design information to create a product model. Any information which is relevant to the use of RP can be added to this model at a component or feature level. The designer is encouraged to think about the design requirements for the RP model and is able to record these in a structured manner which reflects the way the component has been designed. In this way, the RP model requirements are specified more clearly. The product model can then be accessed by the RP operator to extract and use all relevant information to optimise the RP process. Therefore, the designer can have greater confidence that the RP model will meet the specified requirements. This means of achieving the transition from CAD model to RP model will help persuade the designer to use RP as an integral part of the design process.

7.5.2 Ensure Right First Time RP Models

The comprehensive nature of the product model used within the DSS ensures that all the non-geometric information needed to support the use of RP can be made available to the RP operator. Even if the current fields in the database tables do not cover all requirements, additional fields can be added very easily. The requirement for geometric data to be provided is currently met using triangular facets. This is not ideal but it is as accurate as using STL files. The availability of this complete product model allows RP system selection, data access by the RP operator and the correct choice of build parameters to be achieved. This ensures that right first time RP models become the normal expectation for the designer.

7.5.3 Improve Communication between the Designer and RP Operator

The information held in the product model within the DSS is not enough, on its own, to improve communication between the designer and RP operator. What is also needed is the means whereby the RP operator can access the data input by the designer. This could be achieved in two ways. Firstly, tailor-made output files could be generated by the designer and sent to the RP operator. Secondly, the RP operator could access the DSS directly and interrogate the database. The current implementation of the DSS allows for either of these and does actually produce an output file to help the RP operator decide upon optimum build orientation.

7.5.4 Optimise the RP Build Parameters

There are many build parameters which need to be optimised for the various commercial RP systems which are currently available. Algorithms could be written for any of these which would access the data in the DSS product model and use this to calculate optimum parameter values. Only one such algorithm has been created, i.e. the optimisation of build orientation to meet the surface finish requirements for the RP model. The consideration of different requirements for the different features within the component is an essential part of this algorithm. It demonstrates that the DSS can help to optimise RP build parameters in a way that non-feature-based software tools cannot.

7.6 Conclusions

A design support system for rapid prototyping has been created from the specification derived in Chapter 6. It is not fully functional in that it does not contain all the specified modules but it does demonstrate how a feature-based product model can be used to support the designer's use of RP. It allows both geometry and non-geometric design information to be combined in the same database. It can store this data at both a component and feature level, with a hierarchical link between the two. The database structure has been designed to allow future expansion, e.g. the use of surface and curve geometry. A number of software modules have been created which enable data to be entered, manipulated and used to support an orientation optimisation procedure. The use of all these modules has been demonstrated through the use of an example component. This showed how the feature-based approach can solve a problem which would otherwise be very difficult, i.e. the requirement for optimised orientation to achieve different surface finish values on different parts of the component. A sensitivity analysis of the orientation optimisation was also performed which demonstrated how the system provides designers with essential feedback on the effect of their decisions upon the prototyping process. Finally, the DSS was evaluated against the relevant ideal system characteristics identified in chapter 5.

CHAPTER EIGHT

FURTHER WORK

This chapter contains recommendations on how the work undertaken during this research project can and should be continued. Indeed, some further work has already been undertaken by students working under the supervision of the author. Where this has happened, reference has been made to the students' work.

8.1 Enabling the Direct Transfer of Non-geometric Design Information from CAD Systems

The insertion into the database system of design data related to whole components and features is currently achieved using input forms. This is quite time consuming and susceptible to human error. If the designer was using a CAD system that supported FBD and had the capability of attaching non-geometric information to the features, then some of this manual data entry could possibly be avoided. The design information contained within the CAD system product model could be directly transferred to the database system by means of an exchange file. However, as discussed in Chapter 6, there is currently no standard format for representing such data. Nevertheless, some work has been conducted by Chrisp and Geldart which has implemented FBD within AutoCAD together with the ability to create a feature-based data exchange file [126]. The software, which was developed in AutoLisp, enables the designer to create several types of form feature and attach non-geometric information to these. When the CAD model is complete, the designer can ask for an exchange file to be created. An example of such a "feature attribute list" file is shown in Figure 8.1. The feature-based exchange file and AutoCAD solid model would provide the design information required for downstream processes such as rapid prototyping. This work needs to continue so that a direct link between the DSS this CAD system is proved feasible and beneficial.

```
Feature ID: POS_PROFILE_1
Volume Type: POS
NAME: Vol_feat_1
PROFILE: PLINE_pos_profile_1
POSITION: 120.00,110.00,0.00
DIRECTION: 0.00,0.00,1.00
ROTATION: 0.00
HEIGHT: 30.00
HEIGHT_TOLERANCE: 0.1

Feature ID: POS_BOSS____2
Volume Type: POS
NAME: Vol_feat_2
POSITION: 145.00,205.00,30.00
DIRECTION: 0.00,0.00,1.00
RADIUS: 15.00
HEIGHT: 30.00
DIAMETER_TOLERANCE: 0.1
HEIGHT_TOLERANCE: 0.25
POSITIONAL_TOLERANCE: 0.1
MATERIAL: Blue

Feature ID: NEG_HOLE____3
Volume Type: NEG
NAME: Surf_feat_1
POSITION: 200.00,145.00,0.00
DIRECTION: 0.00,0.00,-1.00
RADIUS: 10.00
DEPTH: 30.00
DIAMETER_TOLERANCE: 0.1
POSITIONAL_TOLERANCE: 0.1
SURFACE_FINISH: 50
FUNCTION: location

EOF
```

Figure 8.1 Example of "feature attribute list" file created in AutoCAD.

8.2 Increasing the Range of Data in the System

The geometric data stored in the system at present is restricted to triangular facets which are derived from STL files. However, if the system could support B-rep geometry and topology, then more accurate data could be transferred directly from the CAD model. This would require either the mathematical definition of surfaces and curves to be stored within the system or a high-level link into an actual CAD modelling kernel such as ACIS [146]. The individual surface patches could then be grouped together to form volumetric and surface features. The structure of the database has been created with such an expansion in mind (see figure 7.2). The range of non-geometric data could also be extended. Attributes could be attached to geometry at various levels within the database structure; layer, curve, surface, feature or part. This would enable a much wider range of design information to be included within the product model.

At present, the only information relating to RP process capability is the list of surface finish values which can be obtained for stereolithography. This could be extended to include all the other commercially available RP systems once their surface finish capability has been measured. On a larger scale, the range of capability information for each RP system could be widened to include accuracy, material properties, running costs, etc. The designer would then be able to specify the model's requirements for these attributes. A process which endeavoured to match the model's requirements with system capabilities would enable the designer to make an informed choice of which RP system to use. Some work has already been undertaken in this direction by Bernie [147].

8.3 Increasing the Number of Application Modules

Other application modules could be written to make use of the design information contained within the database. One example of this would be an RP usage advisor. An undergraduate student, working under the author's direction, has developed a simple RP usage advisor which has been incorporated into the latest version of the DSS [148]. This advisor asks the user to answer several pertinent questions regarding the use of RP (see Appendix K). If the user answers "yes" to all of these, the use of RP is recommended. If any negative answers are given, the user is first of all advised to consider the wider implications and then, if the answer is still "no", the use of RP is not recommended. This is obviously an over-simplification of the RP usage advisor which is actually required but it illustrates the principle involved.

Another application module which could be developed is an RP build-time and cost estimator. The program would examine the design requirements and the geometry of the model to be built and use these to produce comparative build-time estimates for several RP systems. The figures produced would not have to be very precise, i.e. within a few percent of the correct time. They would only need to be sufficiently accurate to enable the different processes to be compared. A cost estimate would be obtained by combining the build-time estimates with running costs, material costs and overheads to arrive at comparative costings for building the model using different systems. Again these would not have to be extremely accurate, within 20% of the correct cost would be acceptable.

A third application area would be a rapid prototyping system selector. Indeed, a simple RP selection module has been incorporated into the latest version of the DSS [149]. This module compares the design requirements specified for the RP model (accuracy, strength, surface finish, machinability, timescale, budget and maximum dimensions) to the capabilities of five RP techniques. It uses the relative performance of the RP techniques and the user-defined importance of each requirement to calculate a percentage score for each technique. The user can then investigate the composition of each score to see where a technique's performance is strong or weak. Once again, the RP system selector is not as sophisticated as it could be but it does illustrate how a product model approach can be used.

Two further examples of application modules which could be implemented are an adaptive STL generator and an adaptive slicer. These would work best with a B-rep model of the component as described in section 6.2.1. In both cases, the different accuracies required for different features in the component would be used to determine the accuracy of the RP model to be built. With the adaptive STL generator this would be done by varying the chordal accuracy of the triangular facets according to the accuracy required for the feature being meshed. The adaptive slicer would vary the spacing between layers to be used to built the RP model according to the maximum required accuracy of all the features being sliced. This assumes that the RP process to be used can use variable slice thickness. The STL or slice files created by these modules would be smaller than normal but would still ensure an RP model of adequate accuracy. The use of variable layer thickness would also speed up the RP build time.

The aim of creating an extended system would be to assist designers in all their decisions about the use of RP. It could be used each time a physical model was needed and would thus help to further integrate the consideration of using RP into the design process.

8.4 Enhancing the User Interface of the System

The current user interface is very simplistic and involves quite a lot of memorisation and/or note-taking on the part of the user. The correct order of tasks must be followed and file names must be recorded. Two packages are used simultaneously and the integration between them is far from "seamless". These weaknesses could be overcome by using a specially developed user interface. Such an interface would lead the user through the various tasks involved in using the system and some tasks would be automated. On-line help would be available at every stage and file names would be displayed on-screen for possible selection. The user interface would also act as an "umbrella" for MS-ACCESS and AutoCAD so that the system would appear as an integrated unit to the user. The system would then be at a stage where it could be released for evaluation by a much larger number of people, to solicit their opinions on its functionality. They would be able to use it without requiring the supervision of the author. One way of doing this would be to make the system available on the World Wide Web, either as executable code or as an interactive site. The latest version of the DSS, developed by Jones [149], incorporates a Visual Basic [150] user interface which supports many of these requirements.

8.5 Creating a Commercially Available Version of the System

Once the improvements described above have been implemented, the system will be at a stage where it can be shown to potential partners who could then begin to develop a commercial version. This would not necessarily use the same software packages as the research system but it would use the same structure and methodology. One possibility might be to integrate the software with a turnkey CAD system. The product model database could then contain direct links to the CAD geometric database, hence avoiding the duplication of data. The disadvantage of this would be to limit access to the system to those designers making use of that particular CAD package. An alternative route would be to create a stand-alone system with the capability of data transfer with several popular CAD packages. The direction of future development will depend very much upon what partnerships can be established.

CHAPTER NINE

CONCLUSIONS

In this chapter, the achievements of the project are assessed in regard to the objectives stated in Chapter 1. For each objective, conclusions are drawn as to how it has been met. Also, the original contribution to knowledge made by the research is stated. Finally, to act as an overall conclusion, a brief progress review and validation assessment of the whole project is made.

9.1 To Determine What Links are Required Between the Engineering Design Process and Rapid Prototyping

In Chapters 2 and 3, engineering design and rapid prototyping technologies were described in detail. The iterative nature of the design process, with the need for frequent evaluations, provides an ideal opportunity for the use of physical prototype models. As the design process moves towards production, so the function, and hence requirements, of these models will change. The development of a wide range of RP technologies and materials means that many of the models previously made using alternative methods can now be made more quickly using RP. Also, the speed of creating models using RP has opened up new areas where, previously, model-making had been too slow or expensive. However, some models are not suited to RP and the advancement of computer modelling sometimes offers a cheaper alternative to physical models. Therefore, there is a need to use RP in an effective manner, only when it will bring benefits over the available alternatives.

Chapter 4 shows that, to ensure the effective use of RP, a series of steps need to be executed to provide the optimum transition from design to RP model. It must be determined if RP is appropriate. If so, the most suitable RP system must be selected. All the information required to support the RP process must be available in the correct format. The optimum combination of RP process parameters must be established. These four steps must be considered each time the use of RP is being considered. Each one acts as a link between the design process and RP and each one must be optimised. The links between design and RP having been identified, Chapter 4 went on to describe what software tools have been developed to support these links. A failing of nearly all these tools is their concentration upon using only geometric data to support RP. The culmination of this initial part of the research project was the formulation of the requirement statement at the end of Chapter 4.

9.2 To Design a Computerised System to Support the Designer's Use of Rapid Prototyping

Chapter 5 began with a justification of the need for a design methodology for using RP. This need had been recognised by others but no formalised methodology had ever been created. It was decided that the most effective way of applying the methodology was through the use of a design support system for RP. To develop a specification for this system, both negative and positive approaches were used. On the negative side, the problems caused by not taking RP into consideration during the design process were identified. The system had to ensure that these were avoided. On the positive side, the opinions and requirements of designers using RP were solicited through a questionnaire which received a high response rate of over 45%. The DSS had to meet the commonly agreed requirements of these designers. Using both these positive and negative requirements, the specific objectives of the DSS were drawn up and used as the starting point for the definition of the computerised system, described in Chapter 6.

The central pillar of the DSS was to provide the designer with the ability to access, process and communicate all RP-relevant design information. A feature-based product modelling approach was used to enable all information, both geometric and non-geometric, to be used by the system. The product model was defined by considering the designer's use of RP-related information. Firstly, the information required to support RP was identified. Secondly, the required format of this information was specified. Thirdly, the processes required to use this information for supporting RP were specified in the form of an implementation-independent computer system architecture.

9.3 To Implement the Design Support System and Demonstrate the Benefits its Use will Yield

Once the design support system had been defined, the next stage was to develop an implementation. Chapter 7 describes how a "demonstration system" was implemented using MS-ACCESS and AutoCAD. Several, but not all of the software modules described in Chapter 6 were written. However, the ones which were written enabled feature-based design information to be entered into the system and used to optimise one aspect of the rapid prototyping process. This particular application used feature-based surface finish requirements to calculate the optimum build orientation to achieve best overall surface finish on an RP model. The ability to assign different surface finish requirements to different parts of the model is useful both to the designer and the RP operator. The designer can ask for good surface finishes on functional surfaces and leave other surfaces with an unspecified value. This is a typical requirement for engineering components. The RP operator can now use a build orientation which will take account of varying surface finish requirements on different parts of the model. This avoids the creation of models with unnecessarily smooth surfaces where they are not required. This single application of the feature-based product modelling approach to RP demonstrates that it does yield tangible benefits. Other potential applications have been described in Chapter 8.

9.4 To Identify the Future Research and Development which is Required to Transform the System into a Commercial Package

The fulfilment of this objective is described in Chapter 8. The areas of required further work have been identified and described. It is clear that a significant amount of research and development is needed in the way of improved system functionality and user interface. However, the basic structure of the system is in place and essential information required for an improved implementation is provided in Chapter 6. This work will require many man-months of time and its prompt completion is beyond the capability of a single part-time researcher. For this reason, it is hoped that a small team of personnel will be able to continue work on the system.

9.5 Original Contribution to Knowledge

The use of a feature-based product model to optimise RP is an idea that originated within this research project. This is testified to by several publications during 1995/96 [126, 127, 149] which precede any other published papers promoting this approach. Indeed the only relevant article which has been found prior to this work was one which argued against the use of FBD for RP [72].

The originality of this work is seen through the demonstration that attaching non-geometric design information to geometric features within a product model can bring tangible benefits to the RP process. This has been achieved by creating a computerised system based on a feature-based product model. Such a system is far from unique but it is the first system of this type to cater for design information distinctively tailored to the support of RP, e.g. triangular facets and multi-material components. The availability of a fully-functional version of this system will enable the consideration of RP to be fully integrated into the design process.

9.6 Review of Progress and Validation of Work

This research project has been successful in that it has identified a problem, investigated the weaknesses of current solutions and provided a novel solution to the problem. It has met or provided the potential to meet all of the research objectives and an original contribution to knowledge has been made. It has provided a foundation for future research and has resulted in several journal and conference publications which are listed in Appendix L.

It should be noted that the project has run over a four year period and in some areas has been overtaken by recent developments. Therefore, if the project were to be undertaken in present circumstances, some things would be done differently. Most notably, the ability to embed non-geometric information in feature-based CAD models is now available on a PC hardware platform, e.g. within AutoCAD Release 14. This was not the case in 1995. Hence, some of the programming which was undertaken to link AutoCAD and MS-Access to create a product model would no longer be necessary since this could be accommodated within a standard CAD system. This does not detract from the work that was done but rather serves to validate the direction which was taken since this has now been followed by a major CAD supplier.

References

1 Dixon J.R., Simmons M.K. and Cohrn P. *An Architecture for Application of Artificial Intelligence to Design.* Proc. of 21st Design Automation Conference, IEEE, 1984. pp 634-640.

2 Brown D.C. and Chandrasekaran B. *Expert Systems for a Class of Mechanical Design Activity.* in Knowledge Engineering in Computer Aided Design, Gero J.S. (Ed), Elsevier Science Publishers, 1985. pp 259-290.

3 Sriram D., Stephanopoulos G., Logcher R., Gossard D., Grouleau N., Serrano D. and Navichandra D. *Knowledge-based System Applications in Engineering Design: Research at MIT.* AI Magazine, Fall, 1989. pp 79-95.

4 Liu C.R. and Trappey J.C. *A Structured Design Methodology and Metadesigner: A System Shell Concept for Computer Aided Creative design.* Advances in Design Automation, Vol 1 - Computer Aided and Computational Design, ASME, 1989. pp 309-313.

5 Duhovnik J. *Systematic Design in Intelligent CAD Systems.* Intelligent CAD Systems I: Theoretical and Methodological Aspects, ten Hagen P.J.W. and Tomiyama T. (Eds), Springer-Verlag, 1987. pp224-238.

6 Waldron M.B. *Design Processes and Intelligent Computer Aided Design (ICAD).* in Intelligent CAD III, Yoshikawa H., Arbab F. and Tomiyama T. (Eds), Elsevier Science Publishers, 1991. pp 51-75.

7 Yang J. and Rozenblit J.W. *Case Studies of Design Methodologies: A Survey.* Proc. of AI, Simulation and Planning in High Autonomy Systems, IEEE, 1990. pp 136-141.

8 Smithers T. *AI-based Design versus Geometry-based Design or Why Design Cannot be Supported by Geometry Alone.* Computer-Aided Design, Vol 21, No 3, April 1989. pp 141-150.

9 Colton J.S. and Dascanio J.L. *An Integrated, Intelligent Design Environment.* Proc. of International Computers in Engineering Conference, ASME, 1990. pp 9-15.

10 Maher M.L., Sriram D. and Fenves S.J. *Tools and Techniques for Knowledge Based Expert Systems for Engineering Design.* Advanced Engineering Software, Vol 6, No 4, 1984. pp 178-188.

11 Ohsuga S. *Introducing Knowledge Processing Technology to CADCAM.* Finite Elements in Analysis and Design 1, Elsevier Science Publishers, 1985. pp 255-269.

12 Kinoglu F. and Riley D. *Artificial Intelligence: Expert System Model of the Design Process.* Design News, 3rd March, 1986. pp 149-156.

13 Brown D.C. and Chandrasekaran B. *Knowledge and Control for a Mechanical Design Expert System.* Computer, July, 1986. pp 92-100.

14 Groover M.P. and Zimmers E.W. *CADCAM: Computer Aided Design and Manufacturing.* Prentice/Hall International, 1984.

15 Zeid I. *CAD/CAM, Theory and Practice.* McGraw-Hill, 1991.

16 Sutherland I.E. *Sketchpad: a Man-machine Graphical Communication System.* Proc. of Spring Joint Computer Conference, AFIPS, 1963. pp 329-346.

17 Keast J.E. *Solid Modelling.* Integrated Graduate Development Scheme CAD Module Course Notes, University of warwick, 1987.

18 Dixon J.R., Cunningham J.J. and Simmons M.K. *Research in Designing with Features.* in Intelligent CAD I, Yoshikawa H. and Warman E.A. (Eds), North-Holland, 1989. pp 137-148.

19 Patel R.M. and McLeod A.J. *Engineering Feature Description in Mechanical Engineering Design.* Computer Aided Engineering Journal, Vol 5, No 5, 1988. pp 180-183.

20 Dixon J.R., Libardi E.C., Luby S.C., Vagul M. and Simmons M.S *Expert Systems for Mechanical Design: Examples of Symbolic Representation of Design Geometries.* Engineering with Computers, Vol 2, 1987. pp 29-46.

21 *CADDS 5.* Computervision, Argent Court, Sir William Lyons Road, Coventry, UK.

22 *Pro/ENGINEER.* Parametric Technology, Technology House, Bracknell Beeches, Bracknell, UK.

23 Krause F., Ulbrich A. and Vosgerun F.H. *Feature Based Approach for the Integration of Design and Process Planning Systems.* in Product Modelling for Computer Aided Design and Manufacturing, Turner J. et al (Eds), Elsevier Science Publishers, 1991. pp 285-298.

24 Tomiyama T. and Yoshikawa H. *Knowledge Engineering and CAD.* Proc. of International Symposium on Design and Synthesis, Japan Society of Precision Engineers, 1984. pp 1-6.

25 Tomljanovich M. *Computer and Designer Integration.* in Computer Applications in Production and Engineering, Kimura K. and Rolstadas A. (Eds), Elsevier Science Publishers, 1989. pp 143-151.

26 Kalpakjian S. *Manufacturing Engineering and Technology (Second Edition).* Addison-Wesley, 1992.

27 Wohlers T. *State of the Industry* Proc. of Rapid Prototyping and Manufacturing Conference '93, Dearborn, Society of Manufacturing Engineers, 1993.

28 Jacobs P. *Stereolithography and other RP&M Technologies.* ASME Press, 1996.

29 Miller J.F. *Rapid Prototyping Fact Sheets.* EDS Unigraphics, 800 Tower Drive, Troy, MI 48098, USA.

30 Chua C.K. and Leong K.F. *Rapid Prototyping: Principles and Applications in Manufacturing.* John Wiley & Sons, 1997.

31 Sachs E., Curodeau A., Gossard D., Jee H., Cima M. and Caldarise S. *Surface Texture by 3D Printing.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 56-64.

32 Cima M., Sachs E., Cima L.G., Yoo J., Khanuja S., Borland S.W., Wu B. and Giordano R.A. *Computer-derived microstructures by 3D Printing: Bio and Structural Materials.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 181-190.

33 Dickens P., Pridham M., Cobb R., Gibson I. and Dixon, G. *3D Welding.* Proc. of 1st European Conference on Rapid Prototyping, University of Nottingham, UK, 1992. pp 81-93.

34 Merz R., Prinz F.B., Ramaswami K., Terk M. and Weiss L.E. *Shape Deposition Manufacturing.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 1-8.

35 Konig W., Celiker T. and Herfurth H-J. *Approaches to Prototyping of Metallic Parts.* Proc. of 2nd Euopean Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1993. pp 303-316.

36 Luck L., Bauman F., Keller B. and Wiedemann B. *Material Research and Development for Rapid Prototyping Techniques at the IKP.* Proc. of 3rd Euopean Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 309-326.

37 Kochan D. *Selection and Evaluation of SFM Systems.* Proc. of Towards World Class Manufacturing, International Federation of Information Processing, 1994.

38 Gibson I., Brown D., Cobb S. and Eastgate R. *Virtual Reality and rapid Prototyping: Conflicting or Complementary?* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1993 pp 113-120.

39 Hull C., Feygin M., Baron Y., Sanders R., Sachs S., Lightman A. and Wohlers T. *Rapid Prototyping: Current Technology and Future Potential.* Rapid Prototyping Journal, Vol 1, No1, 1995. pp 11-19.

40 Cheshire D.G., Harrison D.K. and Wormald P.W. *Novel Techniques for Tableware Development.* Proc. of 3rd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 181-190.

41 Allin K.J. *Experimental Stress Analysis of Rapid Prototype Components.* Proc of 2nd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1993. pp 119-129.

42 Cowie J. *Now Boeing's Digital Gamble Must Fly For Real.* Professional Engineering, Vol 7, No10, 1994. pp 10-12.

43 Arthur A., Dickens P.M. and Cobb R.C. *Using Rapid Prototyping to Produce EDM Electrodes.* Rapid Prototyping Journal, Vol 2, No 1, 1996. pp 4-12.

44 Stucker B., Bradley W., Eubank P.T., Norasetthekul S. and Bozkurt B. *Zirconium Diboride/Copper EDM Electrodes from Selective Lase Sintering.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 257-264.

45 Coole T.J., Cheshire D.G. and Newman D.J. *The Application of Rapid Prototyping to the Tableware Industry.* Proc. of 4th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1995. pp 41-53.

46 Hirose M. and Sato S-I *The Design of Virtual Worlds.* Proc. of Design for Manufacturability Conference, American Society of Mechanical Engineers, 1994. pp 13-18.

47 Dani T.H., Fathallah M. and Gadh R. *COVIRDS: An Architecture for a Conceptual Virtual Design System.* Proc. of Design for Manufacturability Conference, American Society of Mechanical Engineers, 1994. pp 19-26.

48 Smyth S. *Personal Communication* General Motors, Midsize Car Division Headquarters, 30001 Van Dyke 2-10, Warren, MI 48090-9020, USA.

49 Gee R.W. *Case Studies in Rapid Prototyping at Sunstrand Electrical Power Systems.* SME Technical Paper (Series) PE, 1993, pp 1-23.

50 Kochan D. *Solid Freeform Manufacturing.* Elsevier, Amsterdam, 1993.

51 Wohlers T. *State of the Industry Reports 1993-1997.* Wohlers Web World, http://lamar.colostate.edu/~wohlers/, 1997.

52 Marcus H.L., Harrison S. and Crocker J. *Solid Freeform Fabrication: an Overview.* American Society of Manufacturing Engineers, Manufacturing Engineering Division, MED, 1996 Vol 4. pp3-9.

53 Smith-Moritz G. (Ed) *Evaluating Rapid Prototyping Systems.* Rapid Prototyping Report, March 1993. pp 3-6.

54 Burns M. *Automated Fabrication* Prentice Hall, Englewood Cliffs, NJ, 1993.

55 Waterman N. *Rapid Prototyping in the USA.* Report on the Overseas Science and Technology Expert Mission to the USA, Institution of Mechanical Engineers/Dept. of Trade and Industry, London, 1993.

56 Schmidt L.D. *Rapid Prototyping Technology: Benchmarking Comparison.* Proc. of 4th International Conference on Rapid Prototyping, University of Dayton, 1993. pp 301-308.

57 Gargiulo E.P. *Stereolithography Process Accuracy User Experience.* Proc. of 1st European Conference on Rapid Prototyping, University of Nottingham, UK, 1992. pp 187-201

58 Lart G. *Comparison of Rapid Prototyping Systems.* Proc. of 1st European Conference on Rapid Prototyping, University of Nottingham, UK, 1992. pp 243-254.

59 Juster N.P. and Childs T.H.C. *A Comparison of Rapid prototyping Processes.* Proc. of 3rd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 35-52.

60 Iuliano L., Ippolito R. and De Filippi A. *A New User Part for Performances Evaluation of Rapid Prototyping Processes.* Proc. of 3rd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 327-339.

61 Jayaram D., Bagchi A., Jara-Almonte C.C. and O'Reilly S. *Benchmarking of Rapid Prototyping Systems - Beginning to Set Standards.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 146- 153.

62 Aubin, R.F. *A World Wide Assessment of Rapid Prototyping Technologies.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 118-145.

63 *Expert Briefing.* - Optimat Ltd., Nasmyth Building, Scottish Enterprise Technology Park, East Kilbride, Glasgow, UK, 1994

64 McMahon C. and Browne J. *CADCAM From Principles to Practice.* Addison-Wesley, Wokingham, UK, 1993.

65 *STL File Format Specification.* 3D Systems Corporation, 26081 Avenue Hall, Valencia, CA 91355, USA.

66 Jamieson R. and Hacker H. *Direct Slicing of CAD Models for Rapid Prototyping.* Rapid Prototyping Journal, Vol 1, No 2, 1995. pp 4-12.

67 *Cubital Facet List (CFL) File Format Specification.* Cubital Ltd., 13 Hasadna Street, P.O.B. 2375, Industrial Zone North Raanana, 43650 Israel.

68 Wang Y., Dong J. and Marcus H.L. *The Use of VRML to Integrate Design and Solid Freeform Fabrication.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 669-676.

69 *Common Layer Interface (CLI), version 1.31.* Brite-Euram Rapid Prototyping Techniques, Project No. BE5278, 1994.

70 *SLC File Format Specification.* 3D Systems Corporation, 26081 Avenue Hall, Valencia, CA 91355, USA.

71 Chalasani K.L. and Bagchi A. *Process Planning Issues in Freeform Fabrication.* American Society of Mechanical Engineers, Production Engineering Division (Publication) PED, Vol 56, 1992. pp 81-92.

72 Kruth J.P. *Materials Ingress Manufacture by Rapid Prototyping Technologies* Annals of CIRP, Vol 40, No 2, 1991. pp 603-614.

73 Muller H., Joppe M. and Sheng X. *Concept for an integrated Rapid Prototyping Process Planning System.* Proc. of 4th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1995. pp 81-94.

74 Phillipson D.K. and Henderson M.R. Rapid *Prototyping Machine Selection Programme*. Proc. of 6th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1997. pp 291-303.

75 Narayanan V., Chua C.K. and Ang B. *A Selection Expert System for Solid Freeform Manufacturing*. Proc. of 2nd International Conference on Computer Integrated Manufacturing, Singapore, 1995. pp 1416-1423.

76 Smith-Moritz G. (Ed) *Interfacing CAD and Rapid Prototyping*. Rapid Prototyping Report, January 1992. pp 4-6.

77 Martin A.D. *ADMesh version 0.95*. Home Page of Anthony D Martin, http://heart.engr.csulb.edu/~amartin/, 1997.

78 Bohn J.H. and Wozny M.J. *Automatic CAD-model Repair: Shell-Closure*. Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1992. pp 86-94.

79 Smith-Moritz G. (Ed) *Imageware Introduces Rapid Prototyping Module (RPM)*. Rapid Prototyping Report, November 1994. pp 6-7.

80 *StlTools*. Igor G. Tebelev, PO Box 4491, Palos Verdes, CA 90274, USA.

81 Fadel G., Crane D., Dooley L. and Geist R. *A Link Between Virtual and Physical Prototyping*. Proc. of Rapid Prototyping and Manufacturing Conference '95, Dearborn, Society of Manufacturing Engineers, 1995.

82 Alciatore D.G. and Wohlers T.T *Importing and Reshaping Digitized Data for Use in Rapid Prototyping*. Rapid Prototyping Journal, Vol 2, No 1, 1996. pp 13-23.

83 *Bridgeworks 3.0*. Solid Concepts Inc., 28231 Avenue Crocker, Unit #10, Valencia, CA 91355, USA

84 *MAGICS 3.01*. Materialise N.V., Kapeldreef 60, B-3001 Heverlee, Belgium.

85 Webb D. and Gerdes V. *Computer-aided Support Structure Design for Stereolithography Models*. Proc. of 5th International Conference on Rapid Prototyping, University of Dayton, USA, 1994. pp 221-228.

86 *STL Manager*. POGO International Inc., 7607 Eastmark Drive, Suite 242, College Station, Texas 77845, USA.

87 Kirschman C.F., Jara-Almonte C.C., Bagchi A., Dooley R.L. and Ogale A.A. *The Clemson Intelligent Design Environment for Stereolithography.* Proc. of 2nd International Conference on Rapid prototyping, University of Dayton, USA 1991. pp 240-245.

88 Kirschman J.S., Kirschman C.F., Fadel G.M. and Greenstein J.S. *The Clemson Intelligent Design Environment for Stereolithography - CIDES 2.0.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 569-576.

89 Dolenc A. and Makela I. *Rapid Tools: A Workbench for Data Transfer and Data Preparation for Rapid Prototyping.* Proc. of 4th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1995. pp 95-103.

90 Suh Y. and Wozny M.J. *Adaptive Slicing of Solid Freeform Fabrication Processes.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 404-411

91 Dolenc A. and Makela I. *Slicing Procedure for Layered Manufacturing Techniques.* Computer-aided Design, Vol 26, No 2, 1994. pp 119-126.

92 Kulkarni P. and Dutta D. *Adaptive Slicing for Parameterizable Surfaces for Layered Manufactuirng.* Proc. of ASME Design Automation Conference, American Society of Mechanical Engineers, New York, USA, 1995. pp 211-217.

93 Sabourin E., Houser S.A. and Bohn J.H. *Adaptive Slicing Using Stepwise Uniform Refinement.* Rapid Prototyping Journal, Vol 2, No 4, 1996. pp 20-26.

94 Vancraen W., Swaelens B. and Pauwels J. *Contour Interfacing in Rapid Prototyping - Tools that Make it Work.* Proc. of 3rd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 25-33.

95 Allen S. and Dutta D. *On the Computation of Part Orientation Using Support Structures in Layered Manufacturing.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 259-269.

96 Frank D. and Fadel G. *Preferred Direction of Build for Rapid Prototyping Processes.* Proc. of 5th International Conference on Rapid Prototyping, University of Dayton, USA, 1994. pp191-200.

97 Kim J.Y., Lee K. and Park J.C. *Determination of Optimal Orientation in Stereolithographic Rapid Prototyping.* Technical Report, Dept. of Mechanical Design and Production Engineering, Seoul National University, Korea, 1994.

98 Cheng W., Fuh J.Y.H., Nee A.Y.C., Wong Y.S. Loh H.T. and Miyazawa T. *Multi-objective Optimization of Part-building Orientation in Stereolithography.* Rapid Prototyping Journal, Vol 1, No 4, 1995. pp 12-23.

99 McClurkin J. and Rosen D. *Build Style Decision Support for Stereolithography.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 627-634.

100 Marsan A.L., Allen S., Kulkarni P. and Dutta D. *An Integarted Software System for Process Planning for Layered Manufacturing.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 661-668.

101 Yu G-B. and Noble D. *The Development of a Laser Build-time Calculation Program using Stereolithographic Apparatus (SLA).* Proc. of 3rd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1994. pp 353-367.

102 Chen C.C. and Sullivan P.A. *Predicting Build-time and the Resultant Cure Depth of the 3D Stereolithography Process.* Rapid Prototyping Journal, Vol 2, No 4, 1996. pp 27-40.

103 Brown S. *Simulation of Solid Freeform Fabrication.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1993. pp 143-149.

104 Bugeda G., Cervera M., Lombera G. and Onate E. *Numerical Analysis of Stereolithography Processes using the Finite Element Method.* Rapid Prototyping Journal, Vol 1, No 2, 1995. pp 13-23.

105 Klocke F., Celi I., Noken S. and Wirtz H. *Stereolithography and Selective Laser Sintering - Process Technology and Simulation for Optimized Part Building.* Proc. of 4th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, UK, 1995. pp 169-183.

106 Flach L., Klosterman D.A. and Chartoff R.P. *A Thermal Model for Laminated Object Manufacturing (LOM).* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 677-688.

107 Yardimci M.A., Guceri S.I. and Danforth S.C. *Thermal Analysis of Fused Deposition.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 689-698.

108 Carleberg P. *Product Model Driven Direct Manufacturing.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1994. pp 270-276.

109 *ISO 10303 STandard for the Exchange of Product data (STEP) Application Protocol 204 - Mechanical Design using Boundary Representation.* International Organization for Standardization, 1, rue de Varembé, Case postale 56, CH-1211, Genève 20, Switzerland.

110 Steger W., Geiger M. and Haller T. *Data Models and Information technology for the Production of Prototypes.* Proc. of 4th International Conference on Rapid Prototyping, University of Dayton, 1993. pp 333-341.

111 Smith-Moritz G. (Ed) *Why is CAD so Bad?* Rapid Prototyping Report, December, 1992. pp 4-7.

112 Smith-Moritz G. (Ed) *How Rapid Prototyping is Changing Product Development.* Rapid Prototyping Report, December 1991. pp 5-7.

113 Ulerich P.L. *Rapid prototyping: Cornerstone of the New Design Process.* in Computers in Engineering Vol 1, Gabriele G.A. (Ed), American Society of Mechanical Engineers, 1992. pp 275-281.

114 Jara-Almonte C.C, Bagchi A., Ogale A.A. and Dooley R.L. *Design Environment for Rapid Prototyping.* American Society of Mechanical Engineers, Design Engineering Division (Publication) DE, Vol 29, 1990. pp 31-36.

115 Crawford R. *Computer Aspects of Solid Freeform Fabrication: Geometry, Process Control and Design.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1993. pp 102-112.

116 Jamieson R. and Hacker H. *Direct Slicing of CAD Models for Rapid Prototyping.* Rapid Prototyping Journal, Vol 1, No 2, 1995. pp 4-12.

117 Smith-Moritz G. (Ed) *Automating Microfabrication.* Rapid Prototyping Report, January 1994. pp 2-4.

118 *Transcript of Interview with Graham Hately.* Bespak Plc, Kings Lynn, Norfolk, UK.

119 *Transcript of Interview with Steve Upcraft.* Rexam Plastic Packaging Ltd., Heanor Gate Industrial Estate, Heanor, Derbyshire, UK.

120 Coole S. *Personal Communication.* Staffordshire University, School of Engineering, Beaconside, Stafford, UK.

121 Pugh S. *Total Design.* Addison-Wesley, Wokingham, UK, 1991.

122 Kjellberg T. and Schmekel H. *Product Modelling and "Information-Integrated" Engineering Systems.* Annals of CIRP, Vol 41, No 1, 1992. pp 201-204.

123 Ghodus P. and Vandorpe D. *Standardization of Product Models using STEP.* Proc. of Symposium on Emerging Technologies and Factory Automation, IEEE, 1995. pp 145-153.

124 Wingard L., Carleberg P. and Kjellberg T. *Enabling Use of Engineering Terminology in Product Models and User Interfaces of CAD/CAM Systems.* Annals of CIRP, Vol 41, No 1, 1992. pp205-208.

125 Gu P. and Chan K. *Product Modelling Using STEP.* Computer-Aided Design, Vol 27, No 3, 1995. pp 163-179.

126 Campbell R.I., Chrisp A.G. and Geldart M. *Using Features to Integrate Design and Rapid Prototyping.* Proc. of 13th International Conference on Production Research, Freund Publishing House, London, 1995. Addendum pp3-6.

127 Campbell R.I. *Using Feature-based Design to Optimise Rapid Prototyping.* Journal of Engineering Design, Vol 7, No 1, 1996. pp 95-103.

128 Gindy N.N.Z. *A Hierarchical Structure for Form Features.* International Journal of Production Research Vol 27, No 12, 1989. pp 2089-2103.

129 Bronsvoort W.F. and Jansen F.W. *Feature Modelling and Conversion - Key Concepts to Concurrent Engineering.* Computers in Industry, Vol 21, 1993. pp 61-86.

130 Palm G. and Shafiee A.M. *Product Model Driven laser Sintering at IVF-KTH.* Proc. of 5th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, 1996. pp 1-13.

131 Owen J. *STEP An Introduction.* Information Geometers Ltd, Winchester, UK, 1993.

132 *ISO 10303 STandard for the Exchange of Product data (STEP) Part 11 - The EXPRESS Language Reference Manual.* International Organization for Standardization, 1, rue de Varembé, Case postale 56, CH-1211, Genève 20, Switzerland.

133 Pratt M. *Personal Communication.* National Institute of Standards and Technology (NIST), Manufacturing Systems Integration Division, Building 220, Gaithersburg, MD 20899-0001, USA.

134 Kennicott P.R. *An Application Reference Model for Layered Manufacturing.* Proc. of Intelligent Manufacturing Systems International Conference on Rapid Product Development, Fraunhofer Institute for Manufacturing Engineering and Automation, Stuttgart, Germany, 1994. pp 451-473.

135 *STEP Vendor Translator Announced Releases.* PDES, Inc., http://www.scra.org/pdesinc/vendor.html, 1997.

136 Doty R. *The Final STEP.* in STEP The Future of Product Data Exchange, Automotive Industry Action Group, Southfield, MI, USA, 1995. pp 16-21.

137 Osorio A. *Estimating Building Times for the STEREOS 300.* EARP (European Action on Rapid Prototyping) Newsletter No 7, 1995. pp 14-16.

138 Reeves P.E. and Cobb R.C. *Reducing the Surface Deviation of Stereolithography Using In-process Techniques.* Rapid Prototyping Journal, Vol 3 No 1, 1997. pp 20-31.

139 *Microsoft Access 2.00.* Microsoft Corporation, One Microsoft Way, Redmond, WA 98052-6399, USA.

140 *AutoCAD Release 12.* Autodesk Inc., 111 McInnis Parkway, San Rafael, California 94903, USA.

141 Cobb R.C., Spencer J.D. and Dickens P.M. *Better Surface Finishing Techniques for RPT is a Must.* Proc. of 2nd Scandinavian Rapid prototyping Conference, Danish technological Institute, Denmark, 1993.

142 Reeves P.E. and Cobb R.C. *The Finishing of Stereolithography Models Using Resin based Coatings.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1995. pp 96-107.

143 Reeves P.E. and Cobb R.C. *Improvements in the Surface Finish of Stereolithography Models for Manufacturing Applications.* Proc. of 1st National Conference on Rapid Prototyping and Tooling Research, Mechanical Engineering Publications, London, 1995. pp 139-149.

144 Reeves P.E. and Cobb R.C. SL *Surface Finish - the Cause, Effect and Hands-free Solution.* Proc. of Future of Model Making International Conference, University of Hertfordshire, UK, 1996.

145 Reeves P.E. and Cobb R.C. *Surface Deviation Modelling of LMT Processes - a Comparative Analysis.* Proc. of 5th European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, 1996. pp 59-75.

146 *ACIS 3D Toolkit.* Spacial Technology Inc., 2425 55th Street, Building A, Boulder, CO 80301-5704, USA.

147 Campbell R.I. and Bernie M.R.N. *Creating a Database of of Rapid Prototyping Capabilities.* Journal of Materials Processing Technology, Vol 61, Nos 1-2, 1996. pp 163-167.

148 Jones K.G. *The Production of a Rapid Rrototyping Decision Support System.* Third Year Project Dissertation, Dept. of Manufacturing Engineering and Operations Management, University of Nottingham, UK, 1997.

149 Jones K.G. and Campbell R.I. *Rapid Prototyping Decision Support System.* Proc. of Solid Freeform Fabrication Symposium, University of Texas at Austin, USA, 1997. pp 551-558.

150 *Visual Basic 4.0.* Microsoft Corporation, One Microsoft Way, Redmond, WA 98052-6399, USA.

APPENDIX A

QUESTIONNAIRE USED FOR SURVEY OF DESIGNERS USING RP

QUESTIONNAIRE ON DESIGNERS' USE OF RP
UNIVERSITY OF NOTTINGHAM

1. General information

- What is the name of your company? ______________________
- How many employees work for the company? ______
- How many employees work in product or tool design? ______
- What products are manufactured by your company?
- What is your position within your company? ________________

2. Use of RP

- How did you first hear about RP?
- Why did you start to make use of RP models?
- How do you currently decide when to use an RP model?
- Under what circumstances would you definitely not consider using RP?
- How many RP models have you had made in the last year? _____
- What did you use these RP models for?
- Would you still have had these models made if RP had not been available? Yes/No
    - If yes, how would these models have been made?
- Do you still make use of other model-making techniques? Yes/No
    - If yes, what percentage of your models are made using RP? _____

- What criteria do you use when evaluating the quality of an RP model?

- What proportion of the RP models that you have had built have been of satisfactory quality?

- What were the reasons for any models not being satisfactory?

- What has been the most important benefit(s) of using RP?

- What (if any) problems have you encountered when using RP?

3. Secondary Processing of RP models

- Have any of your RP models been used for secondary processes? Yes/No

    - If yes, which processes e.g. vacuum casting, investment casting, spray metal tooling?

- Have you used RP models to produce prototype tooling? Yes/No

    - If yes, what secondary process(es) did you use to produce the tooling?

    - If no, have you ever considered doing this? Yes/No

4. Effect of RP upon Design Process

- At what stages of the design process have you made use of RP?

- Have you used RP to evaluate alternative designs? Yes/No

- Have you used feedback obtained from RP models to modify designs? Yes/No

- Has the use of RP changed your design process in any way? Yes/No

  - If yes, how?

- Would you consider RP to be an essential part of your design process? Yes/No

5. Choice of RP system

- Which RP process(es) do you have access to (either within your company or through a service bureau)?

  - Stereolithography
  - Selective laser sintering
  - Laminated object manufacture
  - Fused deposition modelling
  - Solid ground curing
  - Other (please specify)

- Who decides which RP process to use?

- How is the choice of RP process made?

- Who decides what accuracy, surface finish and material will be needed for an RP model?

6. **CAD System**

- What CAD system(s) do you use? ____________________

- What proportion of your design work is done on CAD? ______

- Does your CAD system have a solid modelling capability? Yes/No

    - If yes, what proportion of your CAD work is done using solid modelling? ______

- Does your CAD system have a feature-based design capability? Yes/No

    - If yes, do you make use of feature-based design? Yes/No

- Can non-geometric information e.g. surface finish, be attached to features in your CAD system? Yes/No

    - If yes, have you ever used this facility? Yes/No

7. **Transferring data to RP system**

- How do you transfer part geometry from CAD to RP?

- What problems have you encountered when transferring this information?

- How have you overcome these problems?

- Besides part geometry, what other design information do you provide for the RP operator?

- What medium do you use to transfer this additional information?

8. Relationship with RP service

- Where do you have your RP models produced?

- How long have you used this RP service? _______

- Do you receive any feedback from the RP service when the model is supplied or while it is being built? Yes/No

  - If yes, what sort of feedback?

- Would you describe the relationship between yourself and the RP service to be one of partnership or an "over-the-wall" relationship?

9. Future use of RP

- Do you foresee any new applications of RP in your company? Yes/No

  - If yes, what applications?

- Do you expect the use of RP to grow within your company? Yes/No

- Are there any barriers to the wider use of RP within your company? Yes/No

  - If yes, what barriers?

- How could the use of RP be made easier for the designer?

- How do you intend to keep abreast of developments in RP technology?

THANK YOU VERY MUCH FOR YOUR TIME

APPENDIX B

RESULTS OF SURVEY OF DESIGNERS USING RP

1. General information

How many employees work for the company?

1-10	1
11-50	3
51-100	2
101-500	7
501-1000	4
1001-5000	5
5001+	3
Total	25

How many employees work in product or tool design?

1-5	3
6-10	4
11-20	3
21-50	7
51-100	2
101-200	1
201-500	3
501+	2
Total	25

What products are manufactured by your company?

Aerospace	6
Automotive	3
Consultancy	2
Electrical	6
Medical	2
Others	6
Total	25

What is your position within your company?

Managing Director	1
Technical Director/Chief Engineer	5
Senior/Design Engineer	16
CAD/CAM Manager	2
Development Engineer	1
Total	25

2. Use of RP

How did you first hear about RP?

Magazine	10
Colleagues	4
CAD Vendor	2
Television	2
Other	4
Don't know	3
Total	25

Why did you start to make use of RP models?

Reduce lead-time	12
Reduce cost	2
Improve confidence in design	2
Visualisation	2
Convenience for complex parts	3
Other	4
Total	25

How do you currently decide when to use an RP model?

Timing constraint	9	
Cost constraint	9	
Part complexity	7	
Standard practice	3	
Customer request	3	
Other	11	
Total	42	(Some respondents gave more than one answer)

Under what circumstances do you definitely not consider using RP?

Simple part	6
Not cost effective	3
Minor modification to design	2
Sheet metal parts	2
Never	2
Others	10
Total	25

How many RP models have you made in the last year?

1-5	7
6-10	5
11-20	3
21-50	4
51-100	1
101+	3
Don't know	2
Total	25

What did you use these RP models for?

Form and fit analysis	10	
Customer studies	7	
Design approval	5	
Process definition	3	
Visualisation	3	
Casting patterns	3	
Vacuum casting	4	
Other	8	
Total	43	(Some respondents gave more than one answer)

Would you still have had these models made if RP had not been available?

Yes	16
No	6
Sometimes	3
Total	25

If yes, how would these models have been made?

Conventional	10
Manual6	
CNC	3
Total	19

Do you still make use of other model-making techniques?

Yes	17
No	8
Total	25

If yes, what percentage of your models are made using RP?

1-10%	8
11-20%	0
21-30%	1
31-40%	0
41-50%	1
51-60%	1
61-70%	0
71-80%	3
81-90%	2
91-100%	1
Total	17

What criteria do you use when evaluating the quality of an RP model?

Accuracy	16	
Surface finish	13	
Functionality	6	
Appearance	5	
Strength	2	
Distortion	2	
Stability	2	
Other	3	
Total	49	(Some respondents gave more than one answer)

What proportion of the RP models that you have had built have been of satisfactory quality?

1-70%	0
71-80%	4
81-90%	5
91-100%	15
"Most"	1
Total	25

What were the reasons for any model not being satisfactory?

Poor accuracy	5	
Poor hand finishing	5	
Distortion	3	
Poor surface finish	2	
Incorrect file	2	
Other	5	
Total	22	(Not all respondents gave an answer)

What has been the most important benefit(s) of using RP?

Increased speed	19	
Reduced cost	5	
Design verification	4	
Better communication	2	
Visualisation	2	
Other	6	
Total	38	(Some respondents gave more than one answer)

What (if any) problems have you encountered when using RP?

Durability of models	4	
Lack of accuracy	3	
Poor surface finish	2	
High lead-time	2	
Other	5	
Total	16	(Not all respondents gave an answer)

3. Secondary Processing of RP Models

Have any of your RP models been used for secondary processes?

Yes	25
No	0

If yes, which processes?

Vacuum casting	18	
Investment casting	11	
Spray metal tooling	3	
Direct tooling	2	
Total	34	(Some respondents gave more than one answer)

Have you used RP models to produce prototype tooling?

Yes	8
No	17
Total	25

If yes, what secondary process(es) did you use to produce the tooling

Sand casting	3	
Direct tooling	3	
Spray metal tooling	2	
Other	2	
Total	10	(Some respondents gave more than one answer)

If no, have you ever considered doing this?

Yes	10
No	2
Not yet	5
Total	17

4. Effect of RP upon the Design Process

At what stages in the design process have you made use of RP?

Several	8	
Concept	5	
After layout	2	
Development	2	
Before tooling	4	
Other	3	
Total	24	(Not all respondents gave an answer)

Have you ever used RP to evaluate alternative designs?

Yes	13
No	12
Total	25

Have you used feedback obtained from RP models to modify designs?

Yes	24
No	1
Total	25

Has the use of RP changed your design process in any way?

Yes	15
No	10
Total	25

If yes, how?

More 3D CAD work done	5	
Other	8	
Total	13	(Not all respondents gave an answer)

Would you consider RP to be an essential part of your design process

Yes	17
No	6
Sometimes	2
Total	25

5. Choice of RP system

Which RP process(es) do you have access to?

Stereolithography	25	
Selective laser sintering	8	
Laminated object manufacture	8	
Fused deposition modeling	4	
Solid ground curing	3	
Other	1	
Total	49	(Some respondents gave more than one answer)

Who decides which RP process to use?

Designer	9
Company	6
No choice	5
Project manager	2
RP bureau	2
CAD/CAM manager	1
Total	25

How is the choice of RP process made?

Don't know	12	
End use of model	6	
Cost and time	4	
Company decision	3	
Accuracy	2	
Other	5	
Total	32	(Some respondents gave more than one answer)

Who decides what accuracy, surface finish and material will be needed for an RP model?

Designer	17
RP bureau	2
Both	1
Other	5
Total	25

6. CAD System

What CAD system(s) do you use?

AutoCAD	8
Unigraphics	8
ProEngineer	7
CADDS	4
Catia	4
SDRC	3
Alias	2
Other	5
Total	41

(Some respondents gave more than one answer)

What proportion of your work in done on CAD?

1-70%	0
71-80%	3
81-90%	1
91-100%	20
Don't know	1
Total	25

Does your CAD system have a solid modelling capability?

Yes	23
No	2
Total	25

If yes, what proportion of work is done using solid modelling?

0%	1
1-10%	0
11-20%	1
21-30%	2
31-40%	1
41-50%	0
51-60%	1
61-70%	4
71-80%	0
81-90%	2
91-100%	9
Don't know	2
Total	23

Does you CAD system have a feature-based design capability?

Yes	16
No	3
Don't know	6
Total	25

If yes, do you make use of feature-based design?

Yes	15
No	0
Sometimes	1
Total	16

Can non-geometric information e.g. surface finish, be attached to features in your CAD system?

Yes	7
No	8
Don't know	10
Total	25

If yes, have you ever used this facility?

Yes	3
No	4
Total	7

7. **Transferring data to the RP system**

How do you transfer part geometry from CAD to RP?

STL	10	
IGES	4	
DXF	2	
CAD file	2	
2D drawing	1	
Total	19	(Not all respondents gave an answer)

What problems have you encountered when transferring this information?

None	13	
Poor STL files	3	
Lost data	3	
Incompatibility	3	
Other	4	
Total	26	(One respondent gave two answers)

How have you overcome these problems?

Tried again	4	
Rebuilt lost data	2	
Mesh repair software	2	
Total	8	(Not all respondents gave an answer)

Besides geometry, what other design information to you provide for the RP operator?

2D Drawings	7	
Number required	4	
Material	4	
Accuracy	3	
Surface finish	3	
Timescale	3	
Layer thickness	2	
Orientation	2	
Function	2	
Other	3	
None	6	
Total	39	(Some respondents gave more than one answer)

What medium do you use to transfer this additional information?

Verbally	5	
Email	3	
Courier	3	
Modem	3	
Drawing	2	
Fax	1	
Total	17	(Not all respondents gave an answer)

8. Relationship with RP service

Where do you have your RP models produced?

Bureau	6
Parent company	5
In house	4
Total	25

How long have you used this service?

0-1 years	8
2-3 years	10
4-5 years	6
6+ years	1
Total	25

Do you receive any feedback from the RP service when the model is supplied or while it is being built?

Yes	19
No	6
Total	25

If yes, what sort of feedback?

Problems	10	
Delivery estimate	3	
How model should be changed	3	
Other	5	
Total	21	(Some respondents gave more than one answer)

Would you describe the relationship between yourself and the RP service to be one of partnership or an "over-the-wall" relationship?

Partnership	15
Over-the-wall	5
Neither	4
Both	1
Total	25

9. Future use of RP

Do you foresee any new applications of RP in your company?

Yes	18
No	7
Total	25

If yes, what applications?

Rapid tooling	11	
Metal parts	3	
Other	6	
Total	20	(Some respondents gave more than one answer)

Are there any barriers to the wider use of RP within your company?

Yes	9
No	16
Total	25

If yes, what barriers?

Cost of models	7	
Lack of solid modelling	3	
Other	8	
Total	18	(Some respondents gave more than one answer)

How could the use of RP be made easier for the designer?

Reduce cost	5	
Desktop RP machine	3	
Other	11	
Total	19	(Not all respondents gave an answer)

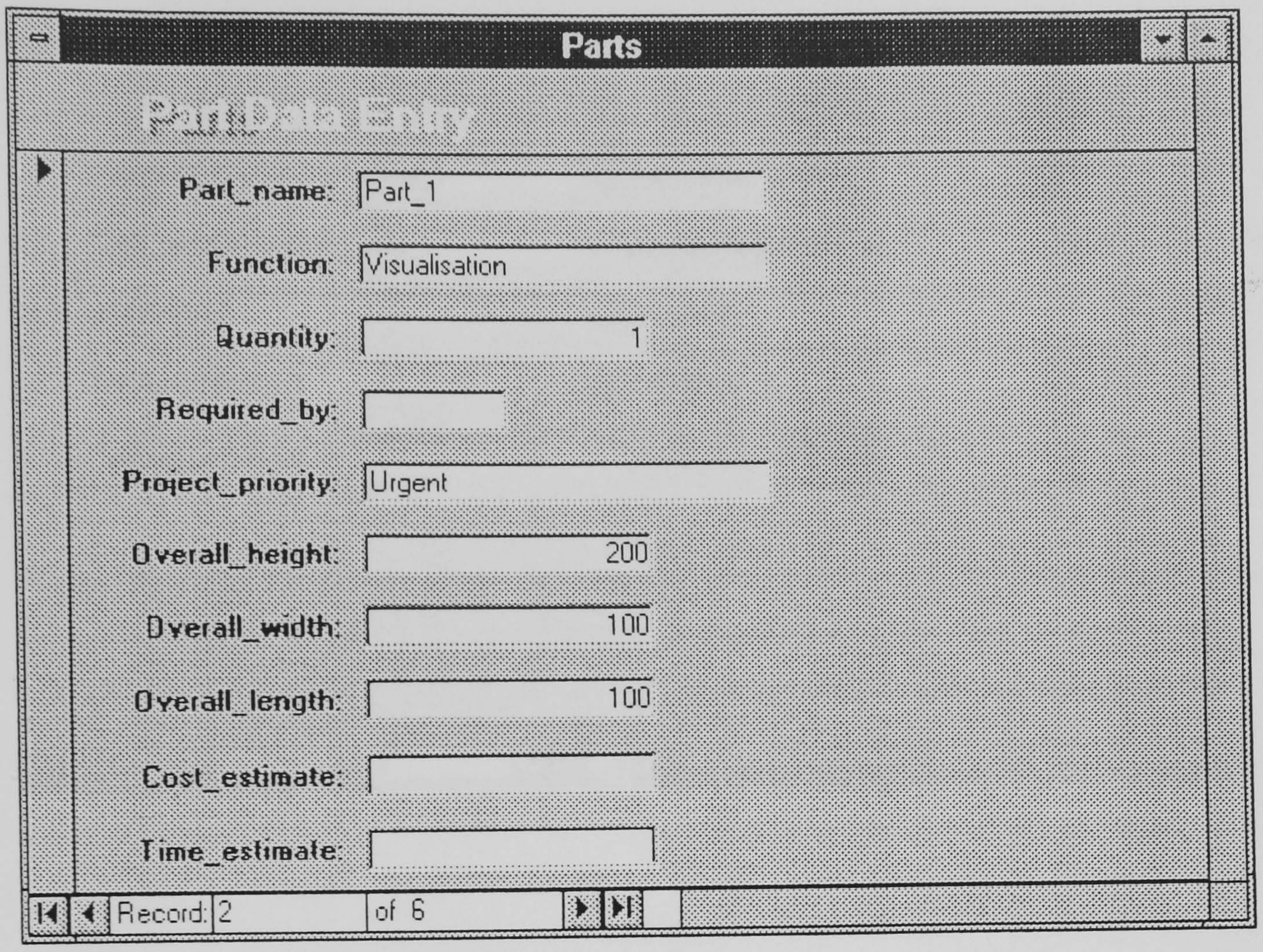
How do you intend to keep abreast of developments in RP technology?

Literature	17	
Conferences	6	
RP companies	3	
Company expert	3	
RP association	3	
Total	32	(Some respondents gave more than one answer)

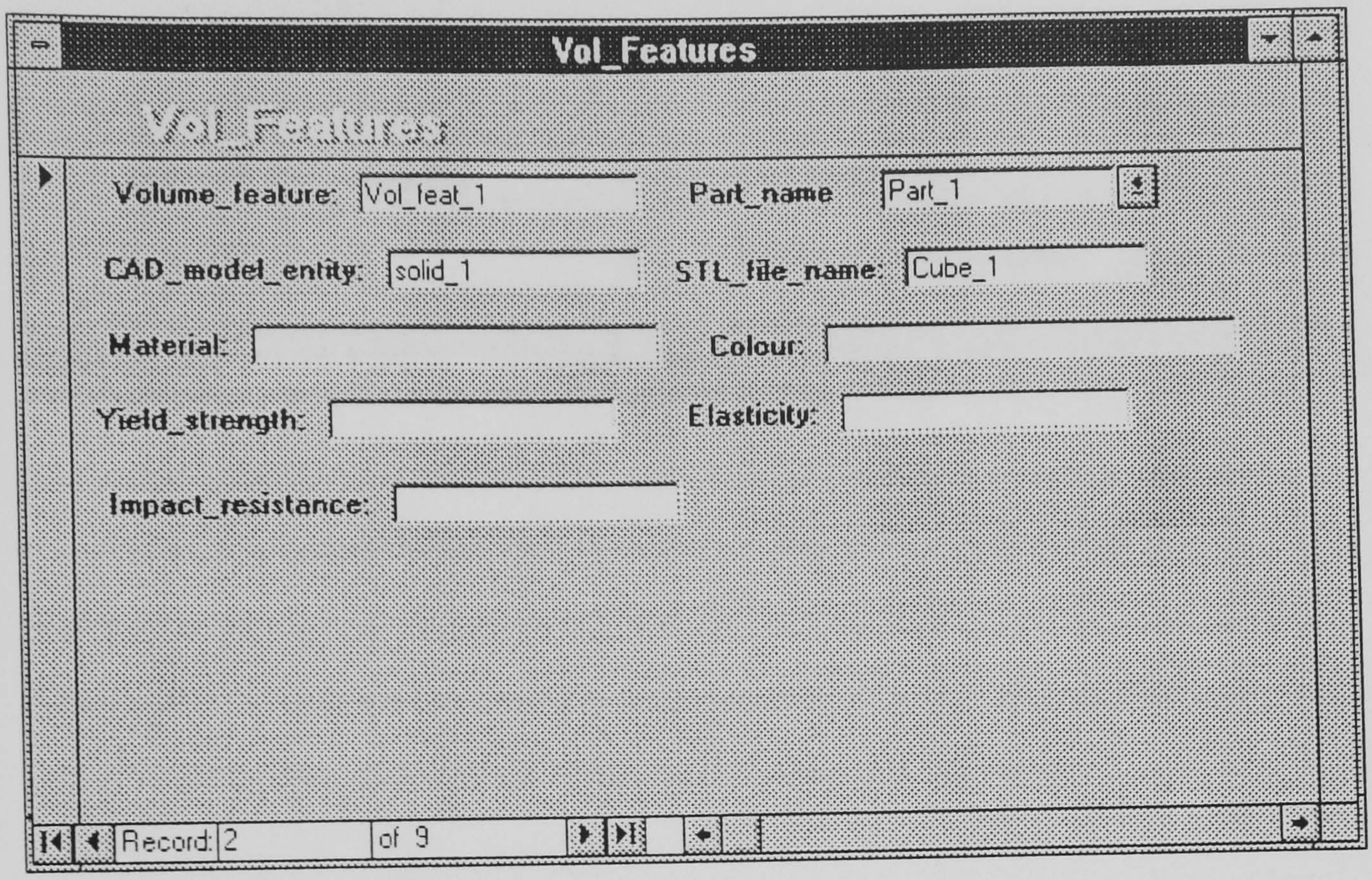
APPENDIX C

DATABASE INPUT FORMS

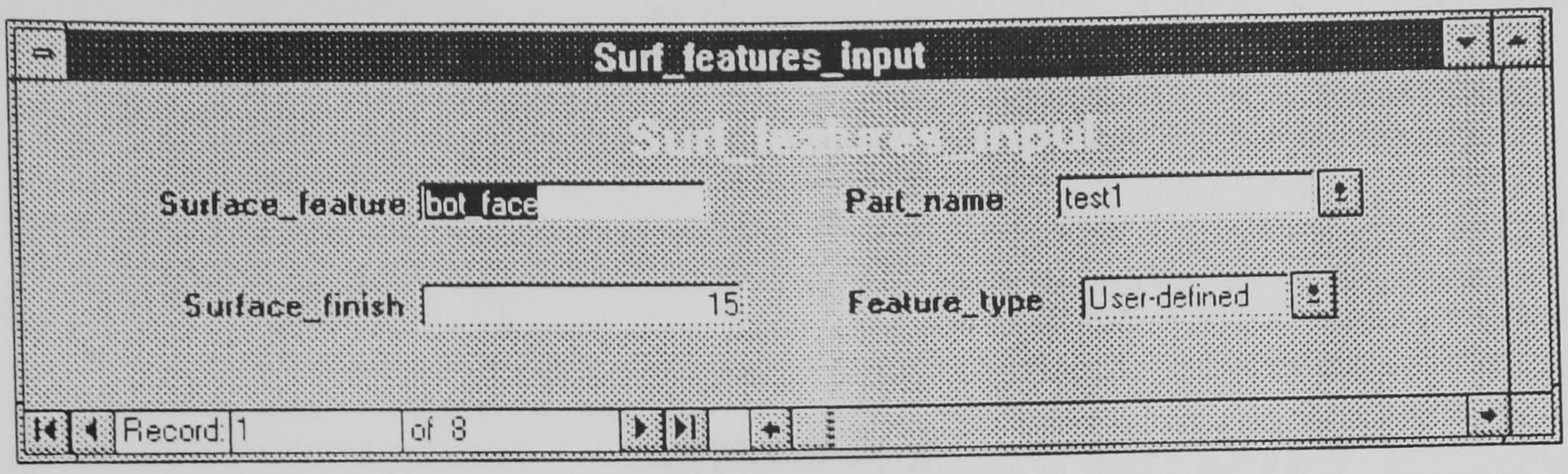
Part Data Entry Form



Volume Feature Data Entry Form



Surface Feature Data Entry Form



APPENDIX D

PROGRAM LISTING FOR “LOAD_STL” MODULE

Access Basic Program Listing for "load_stl" Module

```
Option Compare Database   'Use database order for string comparisons

'Declarations

Dim MyDB As Database
Dim Mytable As Recordset
Dim no_of_facets As Long
Dim normal_x As Single
Dim normal_y As Single
Dim normal_z As Single
Dim first_x As Single
Dim second_x As Single
Dim third_x As Single
Dim first_y As Single
Dim second_y As Single
Dim third_y As Single
Dim first_z As Single
Dim second_z As Single
Dim third_z As Single

'Main function

Function load_stl ()

'Work with current database

Set MyDB = DBEngine.Workspaces(0).Databases(0)

'Work with facets table

Set Mytable = MyDB.OpenRecordset("Facets", DB_OPEN_TABLE)

'Open STL file

Open Forms![convert_stl]![STL_file_name] For Binary As 1

'Open output file

Open Forms![convert_stl]![Output_file_name] For Output As 2

'Read and write number of facets

Get #1, 81, no_of_facets

Write #2, no_of_facets

If no_of_facets = 0 Then Exit Function
```

```
'Read in normal and vertices values for each facet

For I = 0 To (no_of_facets - 1) Step 1
        Get #1, (85 + (I * 50)), normal_x
        Get #1, (85 + (I * 50) + 4), normal_y
        Get #1, (85 + (I * 50) + 8), normal_z
        Get #1, (85 + (I * 50) + 12), first_x
        Get #1, (85 + (I * 50) + 16), first_y
        Get #1, (85 + (I * 50) + 20), first_z
        Get #1, (85 + (I * 50) + 24), second_x
        Get #1, (85 + (I * 50) + 28), second_y
        Get #1, (85 + (I * 50) + 32), second_z
        Get #1, (85 + (I * 50) + 36), third_x
        Get #1, (85 + (I * 50) + 40), third_y
        Get #1, (85 + (I * 50) + 44), third_z

'       Routine to calculate area of facet

        length_a = Sqr(((third_x - first_x) ^ 2) + ((third_y - first_y) ^ 2) +
((third_z - first_z) ^ 2))
        length_b = Sqr(((first_x - second_x) ^ 2) + ((first_y - second_y) ^ 2) +
((first_z - second_z) ^ 2))
        length_c = Sqr(((second_x - third_x) ^ 2) + ((second_y - third_y) ^ 2)
+ ((second_z - third_z) ^ 2))

        value_s = .5 * (length_a + length_b + length_c)

        facet_area = Sqr(value_s * (value_s - length_a) * (value_s - length_b) *
(value_s - length_c))

'       Write values into Facets table in database

        Mytable.AddNew      ' Create new record.

        Mytable("STL_file_name") = Forms![convert_stl]![STL_file_name]
        Mytable("Normal_x") = normal_x
        Mytable("Normal_y") = normal_y
        Mytable("Normal_z") = normal_z
        Mytable("Vertex_1_x") = first_x
        Mytable("Vertex_1_y") = first_y
        Mytable("Vertex_1_z") = first_z
        Mytable("Vertex_2_x") = second_x
        Mytable("Vertex_2_y") = second_y
        Mytable("Vertex_2_z") = second_z
        Mytable("Vertex_3_x") = third_x
        Mytable("Vertex_3_y") = third_y
        Mytable("Vertex_3_z") = third_z
        Mytable("Area") = facet_area
        Write #2, Mytable("Facet_number")
```

```
        Mytable.Update      ' Save changes.

'       Write values multipled by 1000 to output file (to avoid problem with small
'       numbers)

        Write #2, Int(first_x * 1000)
        Write #2, Int(first_y * 1000)
        Write #2, Int(first_z * 1000)
        Write #2, Int(second_x * 1000)
        Write #2, Int(second_y * 1000)
        Write #2, Int(second_z * 1000)
        Write #2, Int(third_x * 1000)
        Write #2, Int(third_y * 1000)
        Write #2, Int(third_z * 1000)

Next I

Mytable.Close

Close 2
Close 1

'       Tell user that processing is finished

Forms![convert_stl]![Processing] = "processing completed"

End Function
```

APPENDIX E

PROGRAM LISTING FOR "FACETSIN" MODULE

AutoLISP Program Listing for "facetsin" Module

```
;*************************************************************
;**                                                   **
;**                   FACETSIN.LSP                        **
;**                                                   **
;**    Reads facet data from ACCESS database and creates graphical entities
**
;**                                                   **
;**         Written by Ian Campbell, last updated 13/5/97           **
;**                                                   **
;************************************************************

;************************ MAIN PROGRAM *******************

(defun C:FACETSIN ()

        (init_facetsin)       ;Initialisation

        (open_file)           ;Open file

        (process_file)        ;Create graphical entities

        (close_file)          ;Close file
)

;********************** INITIALISATION **********************

(defun init_facetsin ()

        (setvar "cmdecho" 0)    ;no echoing of commands

)

;******************* OPEN FILE FOR INPUT *******************

(defun open_file ()

                                        ;user input of input file name...
        (setq file_name (getstring "\nFilename for input: "))
        (setq in_file (open file_name "r"))
)
```

```
;********************** PROCESS_FILE **********************

(defun process_file (/ txthgt count facet pt1 pt2 pt3 ptav firstx firsty firstz
secondx secondy secondz thirdx thirdy thirdz milfirstx milfirsty milfirstz
milsecondx milsecondy milsecondz milthirdx milthirdy milthirdz averagex
averagey averagez diffx diffy diffz hgt)

        (setq count (read (read-line in_file)))          ;read in number of facets

        (while (> count 0)

                (setq facet (read (read-line in_file)))          ;read facet number

                ;read vertices co-ordinates multiplied by 1000

                (setq milfirstx (read (read-line in_file)))
                (setq milfirsty (read (read-line in_file)))
                (setq milfirstz (read (read-line in_file)))
                (setq milsecondx (read (read-line in_file)))
                (setq milsecondy (read (read-line in_file)))
                (setq milsecondz (read (read-line in_file)))
                (setq milthirdx (read (read-line in_file)))
                (setq milthirdy (read (read-line in_file)))
                (setq milthirdz (read (read-line in_file)))

                ;divide all values by 1000

                (setq firstx (/ milfirstx 1000))
                (setq firsty (/ milfirsty 1000))
                (setq firstz (/ milfirstz 1000))
                (setq secondx (/ milsecondx 1000))
                (setq secondy (/ milsecondy 1000))
                (setq secondz (/ milsecondz 1000))
                (setq thirdx (/ milthirdx 1000))
                (setq thirdy (/ milthirdy 1000))
                (setq thirdz (/ milthirdz 1000))

                ;calculate required text height

                (setq averagex ( / ( + firstx secondx thirdx) 3))
                (setq averagey ( / ( + firsty secondy thirdy) 3))
                (setq averagez ( / ( + firstz secondz thirdz) 3))
                (setq diffx (expt ( - firstx averagex) 2 ))
                (setq diffy (expt ( - firsty averagey) 2 ))
                (setq diffz (expt ( - firstz averagez) 2 ))
                (setq txthgt ( / (sqrt (+ diffx diffy diffz)) 20))
                (if (< txthgt 0.1 ) (setq txthgt 0.1))
```

```
                ;input a 3D polyline through three vertices and text at centre of
                ;facet

                (setq pt1 (list firstx firsty firstz))
                (setq pt2 (list secondx secondy secondz))
                (setq pt3 (list thirdx thirdy thirdz))
                (setq ptav (list averagex averagey averagez))
                (command "3dpoly" pt1 pt2 pt3 "C")
                (command "text" ptav txthgt "0" facet)
                (setq count (- count 1))

        )

)

;****************************** CLOSE *********************

(defun close_file ()

        (close in_file)

)

;**************************************************************
;******************** END OF FACETSIN.LSP *******************
;**************************************************************
```

APPENDIX F

PROGRAM LISTING FOR "SELFACET" MODULE

AutoLISP Program Listing for "selfacet" Module

```
;*************************************************************
;**                                                         **
;**                   SELFACET.LSP                          **
;**                                                         **
;**  Selects facet numbers from AutoCAD drawing and dumps list into file
**
;**                                                         **
;**        Written by Ian Campbell, last updated 18/7/97    **
;**                                                         **
;*************************************************************

;********************** MAIN PROGRAM ********************

(defun C:SELFACET (/ facetno )

        (init_selfacet)      ;Initialisation

        (open_files)         ;Open files

        (dump_file)          ;Create list of facets

        (conv_file)          ;Converts strings to numbers

        (close_files)        ;Close files
)

;********************** INITIALISATION **********************

(defun init_selfacet ()

        (setvar "cmdecho" 1)   ;no echoing of commands

)

;****************** OPEN FILE FOR INPUT ******************

(defun open_files ()

        ;user input of output file name...

        (setq file_name (getstring "\nFilename for surface feature: "))
        (setq temp_file (open "temp" "w"))
        (setq out_file (open file_name "w"))
)
```

```
;*********************** DUMP FILE ************************

(defun dump_file (/ entcount entname entlist enttext enttype index )

;       Ask user to select required facets from screen

        (print "Please select facet numbers for surface feature")
        (setq entlist (ssget))                  ; allows user to select entities
        (setq entcount (sslength entlist))      ; counts number of entites selected
        (setq index 0)
        (setq facetno 0)

        (while (< index entcount)               ; while number of entites not reached

                (setq entname (ssname entlist index))     ; take next entity
                (setq entdata (entget entname))           ; find its data
                (setq enttype (cdr (assoc 0 entdata)))    ; find its type
                (if (= enttype "TEXT" ) (setq enttext (cdr (assoc 1 entdata))))
                (if (= enttype "TEXT" ) (print enttext temp_file)) ; if text then
                                                  ;print text value to temp file
                (if (= enttype "TEXT" ) (setq facetno (+ 1 facetno))) ; count
                                                                        ; facets
                (setq index (+ 1 index))
        )

        (close temp_file)
)
;************************ CONVERT ***********************

(defun conv_file (/ string length column number char )

        (setq temp_file (open "temp" "r"))      ; open temp file
        (read-line temp_file)
        (while (> facetno 0)

;       read in a facet number string and convert to equivalent number

                (setq string (read-line temp_file))
                (setq length (- (strlen string) 2))
                (setq column 1)
                (setq number 0)

                (while (> length 1)

                        (setq char (substr string length 1))
                        (if (= char "0") (setq number (+ number (* 0 column))))
                        (if (= char "1") (setq number (+ number (* 1 column))))
                        (if (= char "2") (setq number (+ number (* 2 column))))
                        (if (= char "3") (setq number (+ number (* 3 column))))
```

```
                (if (= char "4") (setq number (+ number (* 4 column))))
                (if (= char "5") (setq number (+ number (* 5 column))))
                (if (= char "6") (setq number (+ number (* 6 column))))
                (if (= char "7") (setq number (+ number (* 7 column))))
                (if (= char "8") (setq number (+ number (* 8 column))))
                (if (= char "9") (setq number (+ number (* 9 column))))

                (setq length (- length 1))
                (setq column (* column 10))
            )

;       write converted number to output file

            (print number out_file)
            (setq facetno (- facetno 1))

        )

(close temp_file)

)

;************************* CLOSE ****************************

(defun close_files ()

        (close out_file)

)

;**********************************************************
;****************** END OF SELFACET.LSP ********************
;**********************************************************
```

APPENDIX G

PROGRAM LISTING FOR "ASSIGN_FACETS" MODULE

Access Basic Program Listing for "assign_facets" Module

```
Option Compare Database  'Use database order for string comparisons

'Declarations

Dim MyDB As Database
Dim Mytable As Recordset
Dim facet_no As Integer

'Main function

Function assign_facets ()

'Work with current database

Set MyDB = DBEngine.Workspaces(0).Databases(0)

'Work with table F_list

Set Mytable = MyDB.OpenRecordset("F_list", DB_OPEN_TABLE)

'SQL command to clear records form F_list

DoCmd RunSQL "DELETE DISTINCTROW F_list.* FROM F_list;"

'Open facet list file file

Open Forms![assign_facets]![Input_file_name] For Input As 1

'Read first line which is empty due to the wat AutoLisp writes data

Input #1, newline

'Read in each facet number and write into F_list table

Do While Not EOF(1)
    Input #1, facet_no
    Mytable.AddNew     ' Create new record.
    Mytable("facet_no") = facet_no
    Mytable.Update     ' Save changes.
Loop

Mytable.Close
```

```
'SQL command to look up in table Facets all the facets listed in F_list and to
'write the name of the facet list file in the surface_feature_name field

DoCmd RunSQL "UPDATE DISTINCTROW F_list INNER JOIN Facets ON
F_list.facet_no = Facets.Facet_number SET Facets.Surface_feature =
[Forms]![assign_facets]![surface_feature_name];"

Close 1

End Function
```

APPENDIX H

PROGRAM LISTING FOR "CALC_SURF_FIN" MODULE

Access Basic Program Listing for "calc_surf_fin" Module

```
Option Compare Database   'Use database order for string comparisons

'Declarations

Dim MyDB As Database
Dim MyTable As Recordset
Dim DataTable As Recordset
Dim Row As Long
Dim Value, Facet, Worstfacet, Count, Average, Area, Total_area As Single
Dim Vx, Vy, Vz, Xang, Yang, Ax, Ay, Vxnew, Vynew, Vznew, Vxy, Angle
As Single
Dim Actual, Surfin, Ratio, Ratiomax, Bestax, Bestay, Bestsol As Single
Dim Problem As String

'Main function

Function calc_surf_fin ()

'Work with current database

Set MyDB = DBEngine.Workspaces(0).Databases(0)

'SQL command to create a list of facets with surface finish values for current
'part in the form of a table called Surf_fin_list

DoCmd RunSQL "INSERT INTO Surf_fin_list ( Part_name, Surface_feature,
Surface_finish, Facet_number, Normal_x, Normal_y, Normal_z, Area )
SELECT DISTINCTROW Parts.Part_name, Surf_features.Surface_feature,
Surf_features.Surface_finish, Facets.Facet_number, Facets.Normal_x,
Facets.Normal_y, Facets.Normal_z, Facets.Area FROM (Parts INNER JOIN
Surf_features ON Parts.Part_name = Surf_features.Part_name) INNER JOIN
Facets ON Surf_features.Surface_feature = Facets.Surface_feature WHERE
((Parts.Part_name=[Forms]![calc_surf_fin]![part_name]));"

'Work with Surf_fin_list table

Set MyTable = MyDB.OpenRecordset("Surf_fin_list", DB_OPEN_TABLE)

'Work with table containing surface finish values for particular process

Set DataTable =MyDB.OpenRecordset(Forms![calc_surf_fin]![Process_name],
DB_OPEN_TABLE)

'Open an output file

Open Forms![calc_surf_fin]![Output_file_name] For Output As 1
```

```
'Set best solution to very high value

Bestsol = 100

'Set initial X angle to zero

Xang = 0

'Loop to increment through rotation angles about x axis

Do While Xang <= 180

        'Set initial Y angle to zero

        Yang = 0

        'Loop to increment through rotation angles about y axis

        Do While Yang <= 180

                'Move to first facet in Surf_fin_list table

                MyTable.MoveFirst

                'Set intitial values

                Ratiomax = 0
                Count = 0
                Total_area = 0
                Average = 0
                Problem = "ok"

                'Convert degrees to radians

                Ax = Xang * .017453292
                Ay = Yang * .017453292

                'Loop to increment through every facet in Surf_fin_list table

                Do While Not MyTable.EOF

                        ' Move to first record in data table

                        DataTable.MoveFirst

                        'Read facet number and its surface finish value

                        Facet = MyTable("Facet_number")
                        Surfin = MyTable("Surface_finish")
```

```
'Read facet normal vectors and area

Vx = MyTable("Normal_x")
Vy = MyTable("Normal_y")
Vz = MyTable("Normal_z")
Area = MyTable("Area")

'Calculate new normal vectors after rotation

Vxnew = (Vx * Cos(Ay)) + (((Vz * Cos(Ax)) + (Vy *
Sin(Ax))) * Sin(Ay))
Vynew = (Vy * Cos(Ax)) - (Vz * Sin(Ax))
Vznew = (((Vz * Cos(Ax)) + (Vy * Sin(Ax))) *
Cos(Ay)) - (Vx * Sin(Ay))
Vxy = Sqr((Vxnew * Vxnew) + (Vynew * Vynew))

'Calculate angle of normal to vertical and set to
'value between 0 and 180 degrees

Angle = ((Atn(Vxy / (Vznew + .0000001))) * 57.3)
If (Angle <= 0) Then Angle = Angle + 180

'Look-up table for actual surface finish

If (Angle > 0 And Angle <= 5) Then Row = 0
If (Angle > 5 And Angle <= 10) Then Row = 1
If (Angle > 10 And Angle <= 15) Then Row = 2
If (Angle > 15 And Angle <= 20) Then Row = 3
If (Angle > 20 And Angle <= 25) Then Row = 4
If (Angle > 25 And Angle <= 30) Then Row = 5
If (Angle > 30 And Angle <= 35) Then Row = 6
If (Angle > 35 And Angle <= 40) Then Row = 7
If (Angle > 40 And Angle <= 45) Then Row = 8
If (Angle > 45 And Angle <= 50) Then Row = 9
If (Angle > 50 And Angle <= 55) Then Row = 10
If (Angle > 55 And Angle <= 60) Then Row = 11
If (Angle > 60 And Angle <= 65) Then Row = 12
If (Angle > 65 And Angle <= 70) Then Row = 13
If (Angle > 70 And Angle <= 75) Then Row = 14
If (Angle > 75 And Angle <= 80) Then Row = 15
If (Angle > 80 And Angle <= 85) Then Row = 16
If (Angle > 85 And Angle <= 90) Then Row = 17
If (Angle > 90 And Angle <= 95) Then Row = 18
If (Angle > 95 And Angle <= 100) Then Row = 19
If (Angle > 100 And Angle <= 105) Then Row = 20
If (Angle > 105 And Angle <= 110) Then Row = 21
If (Angle > 110 And Angle <= 115) Then Row = 22
If (Angle > 115 And Angle <= 120) Then Row = 23
If (Angle > 120 And Angle <= 125) Then Row = 24
```

```
If (Angle > 125 And Angle <= 130) Then Row = 25
If (Angle > 130 And Angle <= 135) Then Row = 26
If (Angle > 135 And Angle <= 140) Then Row = 27
If (Angle > 140 And Angle <= 145) Then Row = 28
If (Angle > 145 And Angle <= 150) Then Row = 29
If (Angle > 150 And Angle <= 155) Then Row = 30
If (Angle > 155 And Angle <= 160) Then Row = 31
If (Angle > 160 And Angle <= 165) Then Row = 32
If (Angle > 165 And Angle <= 170) Then Row = 33
If (Angle > 170 And Angle <= 175) Then Row = 34
If (Angle > 175 And Angle <= 180) Then Row = 35

'Move to selected row in data table and read value

DataTable.Move Row
Actual = DataTable("Value")

'Calculate ratio between actual and required surface
finish

Ratio = Actual / Surfin

'Keep note of worst ratio and facet where this occurs

If (Ratio > Ratiomax) Then Worstfacet = Facet
If (Ratio > Ratiomax) Then Ratiomax = Ratio

'Calculate weighted average value of ratio

Count = Count + 1

Average = ((Average * Total_area) + (Ratio * Area)) /
(Total_area + Area)
Total_area = Total_area + Area

'Move to next record in Surf_fin_list table and loop back

MyTable.MoveNext

Loop

'If actual surf fin is greater than required for any facet then
indicate a problem

If (Ratiomax > 1) Then Problem = "problem"
```

```
                'Write average surface finish ratio, rotation angles, worst
                'surface finish ratio, worst facet and "problem" to output file

                Write #1, Average, Xang, Yang, Worstfacet, Ratiomax,
Problem

                'Keep note of rotation angles with lowest average ratio

                If (Average < Bestsol) Then Bestax = Xang
                If (Average < Bestsol) Then Bestay = Yang
                If (Average < Bestsol) Then Bestsol = Average

                'Increment Y angle and loop back

                Yang = Yang + 5

        Loop

        'Increment X angle and loop back

        Xang = Xang + 5

Loop

'Write best angles to output file

Write #1, "Best X angle and Y angle are", Bestax, Bestay
Forms![calc_surf_fin]![Xang] = Bestax
Forms![calc_surf_fin]![Yang] = Bestay

Close 1

MyTable.Close
DataTable.Close

'SQL commnad to empty Surf_fin_list ready for next time module is called

DoCmd RunSQL "DELETE DISTINCTROW Surf_fin_list.* FROM
Surf_fin_list;"

End Function
```

APPENDIX I

EXAMPLE OF NEUTRAL FILE CONTAINING FACET DATA

Example of Neutral Facet File (shortened)

12	(number of facets)
663	(facet nuber)
10000	(first x value)
10000	(first y value)
10000	(first z value)
10000	(second x value)
0	(second y value)
0	(second z value)
10000	(third x value)
10000	(third y value)
0	(third z value)
664	(next facet)
10000	
10000	
10000	
10000	
0	
10000	
10000	
0	
0	
665	
10000	
10000	
10000	
10000	
10000	
0	
0	
10000	
0	
666	
0	
10000	
0	
0	
10000	
10000	
10000	
10000	
10000	
.	
.	
.	
.	
.	
.	

APPENDIX J

EXAMPLE OF OUTPUT FILE WITH ORIENTATION VALUES

Example of Output File (shortened)

```
.702417727582504,   0,     0,     791,   1.68,   "problem"
.679849318571048,   0,     5,     791,   1.68,   "problem"
.672354642869662,   0,     10,    837,   1.6,    "problem"
.707316492599027,   0,     15,    837,   1.67,   "problem"
.674661717522346,   0,     20,    839,   1.6,    "problem"
.676200453530514,   0,     25,    836,   1.6,    "problem"
.676754233768428,   0,     30,    836,   1.67,   "problem"
.639440416186295,   0,     35,    837,   1.6,    "problem"
.641491365951386,   0,     40,    834,   1.6,    "problem"
.630682449373435,   0,     45,    836,   1.67,   "problem"
.618196206455709,   0,     50,    836,   1.6,    "problem"
.613240364737681,   0,     55,    831,   1.6,    "problem"
.640896525569451,   0,     60,    834,   1.67,   "problem"
       .            .      .      .      .       .
       .            .      .      .      .       .
.416989341781684,   45,    135,   845,   1.17,   "problem"
.399652871726105,   45,    140,   845,   1.17,   "problem"
.380939638981562,   45,    145,   843,   1.07,   "problem"
.410949547810325,   45,    150,   843,   1.07,   "problem"
.414027215660877,   45,    155,   843,   1.07,   "problem"
.      .            .      .      .      .       .
                    .      .      .      .       .
. 407810204712362,  55,    135,   845,   1.07,   "problem"
.397922060079624,   55,    140,   845,   1.07,   "problem"
.404506738914734,   55,    145,   845,   1.07,   "problem"
.408323928748035,   55,    150,   804,   .96,    "ok"
.411397151860743,   55,    155,   804,   1.12,   "problem"
.434965038007989,   55,    160,   785,   1.28,   "problem"
.448695505586906,   55,    165,   785,   1.6,    "problem"
       .            .      .      .      .       .
       .            .      .      .      .       .
       .            .      .      .      .       .
       .            .      .      .      .       .
.676200453530514,   180,   155,   836,   1.6,    "problem"
.674661717522346,   180,   160,   839,   1.6,    "problem"
.707316492599027,   180,   165,   837,   1.67,   "problem"
.672354642869662,   180,   170,   837,   1.6,    "problem"
.679849318571048,   180,   175,   791,   1.68,   "problem"
.702417727582504,   180,   180,   791,   1.68,   "problem"
"Best X angle and Y angle are",     45,    145
```

APPENDIX K

RP USAGE ADVISOR QUESTIONS FROM LATEST VERSION OF DSS FOR RP

RP Usage Advisor - questions on suitability of using RP for a particular component:-

1. Will you require a physical model of this component at sometime during the design process?

2. Is it important that this model is made as quickly as possible?

3. Does the complexity of this component make it difficult to produce a model using CNC machining?

4. Can you produce a CAD solid model for the design of this component?

5. Do you have ready acces to rapid prototyping facilities?

APPENDIX L

PUBLICATIONS

Publications Resulting form Research:-

1. Campbell R.I. & Bernie M.R.N. *Creating a Database of Rapid Prototyping System Capabilities.* Journal of Materials Processing Technology, Vol 61, No 1-2, 1996. pp163-167.

2. Campbell R.I. *Using Feature-based Design to Optimize Rapid Prototyping.* Journal of Engineering Design, Vol 7, No 1, 1996. pp95-103.

3. Campbell R.I., Chrisp A.G. & Geldart M. *Using Features to Integrate Design and Rapid Prototyping. Proc.* 13th International Conference on Production Research, Freund Publ. House, London, 1995. Addendum pp 3-6.

4. Campbell R.I. *Design for Rapid Prototyping; Developing a Methodology.* Proc. of 10th National Conference on Manufacturing Research, Loughborough Univ. of Technology, 1994. pp 521-525.