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PHD

The early cost estimation of injection moulded components

Hosseini-Nasab, Hasan

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The Early Cost Estimation of Injection Moulded Components

Submitted by Hasan Hosseini-Nasab

For the degree of

Doctor of Philosophy

of the University of Bath

December 2002

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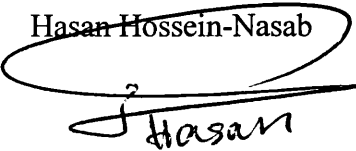
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Hasan Hossein-Nasab

A handwritten signature in black ink, appearing to read 'Hasan', is written over a horizontal line. The line is part of a larger scribble that also encompasses the printed name 'Hasan Hossein-Nasab' above it.

December 2002

Research Supervisors:

Dr. A. R. Mileham

Dr. L. B. Newnes

School of Mechanical Engineering

University of Bath

Summary

This research focuses on a new methodology for the cost estimation of injection moulded products, which enables designers to estimate the cost of the product at the early design stage, with minimal product information and little or no experience of the intended production process.

The method uses potentially generic features to construct injection moulded products, through a CAD system. The key generic features were derived from the analysis of a large data set of injection moulded products and used to develop new products and to estimate their cost.

Two software packages have been utilised to illustrate the methodology, namely; Ideas and FoxPro. Ideas has been used for designing the injection moulded product's generic features, and to develop new injection moulded products. FoxPro interpreter programs have been developed to capture the Ideas output files, filtering out any redundant data and keeping only the information necessary for the cost estimation process. A FoxPro material database for injection moulded products has also been developed to facilitate the process of material selection.

The cost is then estimated using the information gained from the product and a series of parametric equations, developed and validated by Currie at the University of Bath (Currie, 1996).

The proposed methodology is fast and easy to use, and provides an on screen concurrent cost estimation for injection moulded products.

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Nomenclature

CAD	Computer Aided Design
ABC	Activity Based Cost
STEP	Structural Technology Evaluation Program
ACCEM	Advanced Composite Cost Estimating Models
BGA	Ball Grid Array
DCA	Direct Chip Attach
CORA	Customer Order Relaying Assistant
GT	Group Technology
WWW	World Wide Web
CSG	Constructive Solid Geometry
CAMPS	Computer Aided Material and Process Selector
CAM	Computer Aided Manufacturing
CMS	Cambridge Material Selector
IMCEP	Injection Moulding Cost Estimating Program
ABS	Acrylonitrile Butadiene Styrene

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Chapter 1

Introduction

1.1 Designs and Manufacturing Cost

It is well known that the cost of manufacturing a new product is one of the key competitive points for manufacturing companies that are faced with rapid change. Consequently, producing products at minimal cost and at acceptable levels of quality is a necessary step in keeping companies in worldwide competition [Weustink, 2000]. The final product cost is affected by many cost variables such as the products physical structure, functional properties, complexity, material usage, and the manufacturing processes to be used all of which can change throughout the design process.

Design is a set of activities from the establishment of a product requirement specification to the generation of the information necessary for making the product [Cross, 1994]. There are many definitions of design, each referring to a special application of design but in the majority of cases, design is defined as a new solution to a problem, which is performed in the following four stages. [Deter, 1991; Ashley, 1995; Shigley, 1985; Cross, 1994; Groover et al, 1984]

Stage 1 – recognition of need,

Stage 2- conceptual design,

Stage 3- preliminary design,

Stage 4- detailed design

Recognition of need is defined as being aware of the necessary information about the design requirement, the restrictions imposed and describing these in a specification. Conceptual design involves the creation of the functions, which conform to the design specification, and lead to the development of solutions. In the preliminary stage, the conceptual solutions are refined and developed in more detail, problems are resolved and weak aspects are eliminated. In the detailed design stage, the materials specification, dimensions, tolerances and surface condition are specified in the fullest possible detail for manufacturing.

As the design process proceeds, the product costs are committed. When the design process has been completed, the costs of the product are virtually locked in, and most opportunities of reducing them through design, have passed. Research concludes that during the design process, up to 75% of the product cost is committed [Amitabha, 1997; Basson, 1999; Weustink, 2000] and also during the conceptual design stage up to 50% of the avoidable cost are generated and locked in [Clark, 1979; Corbett, 1986; Mileham, 1992]. Therefore, it is necessary to focus on the conceptual design stage of a new product, as the greatest reduction in the product cost can be obtained during this stage [Sumaira, 1998; Chen, 1999; Veldsman, 2000].

1.2 Conceptual Design

Conceptual design can be defined as a set of activities in the early design process where the concept of a product is established [Shaw, 2000]. The concept of the product can include for example an overall shape, the main feature or material type. For a new product, cost is directly related to the concept adopted, therefore the conceptual design

can be the most important stage of the product design process, because, it is at this stage that the main cost of the product is formatted. Decisions at the conceptual design stage also have an effect on the preliminary and detailed design stages and relate to decisions that may change the products manufacturability and manufacturing cost. However, at the conceptual design stage there is limited knowledge about the product, but to make cost effective decisions and to keep the product cost low, it is necessary to invest significant amounts of time and effort at this stage of the design process.

1.3 Conceptual Information

The importance of available information for decision-making is generally recognised today. Decision-making is difficult or has a low accuracy level if no information or little information is available. As conceptual design is an activity at the early stage of new product design, the information available is limited and typically consists of general features, material type and production volume [Currie et al, 1992]. Having this information leads the designer to many possible definitions and decisions for producing the product, but in many situations this information may not be helpful for making decisions about cost. A possible way of cost estimating is by using historical information from a similar design however; the usefulness of the historical information is dependent on the degree of the similarity between the old and new product and the time gap between the designs [Ariffin, 1997].

Conceptual information, historical data and the designers experience are typically the main information that is available for new product development. For new products,

usually there is not enough historical information available and not all designers are familiar with manufacturing processes. This leads to an unacceptable level of uncertainty for cost estimating. To reduce this uncertainty, researchers have demonstrated a wide variety of cost estimating techniques, which are discussed in the following sections of this thesis. Many of these techniques are aimed at cost estimation at the concept stage of design, which is also the focus of this research.

1.4 Conceptual Cost Estimation

Conceptual cost estimation is concerned with the prediction of the costs of a set of activities that are needed to produce a product, using the information available at the conceptual stage of product design. Usually, the cost information available at the conceptual stage of design is limited. For the majority of new products, cost information can only be gained at the detailed design stage and for some new products, a series of activities are needed that are new to the company. It is claimed that the accuracy of a cost estimate improves with the volume of the information available [Corbett, 1986] and as only basic information is available at the concept stage, the cost estimate tends to be inaccurate. However, as stated, the majority of product cost is locked into the product, at the conceptual stage of design [Chen 1999; Sumaira, 1998]. Many approaches have been developed to solve this problem. These are detailed in the following sections. In this research, a new method of concurrent cost estimation is proposed to enable designers to estimate the product cost at the conceptual stage of design.

1.5 Concurrent Cost Estimation

Traditionally, a new product has been developed using a sequential engineering approach to design, which begins with a new product idea and is finalised with the manufacturing stage. It is well known that this traditional approach takes a lot of time and in most cases the traditional designs are difficult to edit or change. This is because the design process deals with numerous variables and changing one, could have an effect on the others. Today, almost all designers use computers for developing new designs. Current computers have significant ability to store, retrieve, and manipulate the necessary data for product design. The use of computers in design also provides an environment, which in the future should enable concurrent product cost estimation. In other words, as the process of the product design proceeds, the relevant information such as the main features and dimensions are stored in files and depending on the software that is used for the design process, this information could be retrieved in some way and be used for cost estimation from concept through to the detailed stage of design. Developing such a concurrent cost estimating system is the subject of the research in this thesis.

There are numbers of different computer aided design (CAD) software packages that can be used for the design process. Typically, each has been developed to meet a specific need or is aimed at a specific area of design. For this research work, the Ideas software package [SDRC, 2001] that is considered to be a powerful design tool has been used for the product design. Using this package enables designers to design a wide variety of products, and import and export files from/to most other design packages

using a variety of neutral formats. It should be noted that although a particular package has been selected the rules and ideas for this research are transferable between packages, which can provide the same output information.

For a concurrent cost estimation to be made simultaneously with a product design the information held within the Ideas output files can be used. From these files, product dimensions and volume can be extracted, which provide the basic information required for cost estimation at the conceptual stage of design.

As there are many manufacturing processes that could be used to produce a product and the selection of a manufacturing process is a multi-attribute decision making process, there is a need to focus on one manufacturing process in this research to develop a reliable cost estimation. Injection moulding has been chosen as the process to develop a cost estimation system for this research work. It has been chosen because a significant proportion of today's products are manufactured using this process i.e. products such as computer enclosures, CD cases, mobile phone cases, etc. In addition, research indicates that there has been a tremendous increase in the demand for injection moulded products over the past several years [Sors, 1998; Ibarhim, 1999]. Generally, injection moulding is the most commonly used process for moulding plastics [Radonoti, 2000]. The process is very economical for mass production and gives a very low unit production cost. Complex shapes can be produced and the diversity of shapes is infinite [Sors, 1999]. Thermoplastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polycarbonate (PC), Polybutylene Terephthalate (PBT) and acrylonitrile butadiene styrene (ABS) are the most commonly used raw materials for injection moulded products.

There are numerous cost variables for an injection moulded product but generally they can be classified into product information, material type, machine information and mould information. For this research, product information such as product features, component volume and also material type are considered as the main factors for developing a concurrent conceptual cost estimation system. This is because the product features and the material specification have a significant effect on the other variables such as the mould features, machine type and cycle time. In addition, designers are involved with the product features and material type at the conceptual stage of design.

Besides the product features, the time the product takes to cool down in the mould and become handle-able is one of the main cost factors for an injection moulded product. Product cooling time is related to melt temperature, mould temperature, demould temperature, the thermal diffusivity of the mould and the products maximum wall thickness [Fenner; 1979, Liner, 1985]. The relationship between the cooling time and maximum wall thickness is shown in figure 1.1 for the PC/ABS and PBT materials. The cooling time increases in relationship to almost the square of maximum wall thickness and thus thickness has a significant influence on the costs of injection moulded products.

The author of this thesis describes a new system for identifying a products maximum wall thickness during the conceptual design stage. In this system, it is suggested that the designer performs the product design through the selection of a series of proposed basic shapes.

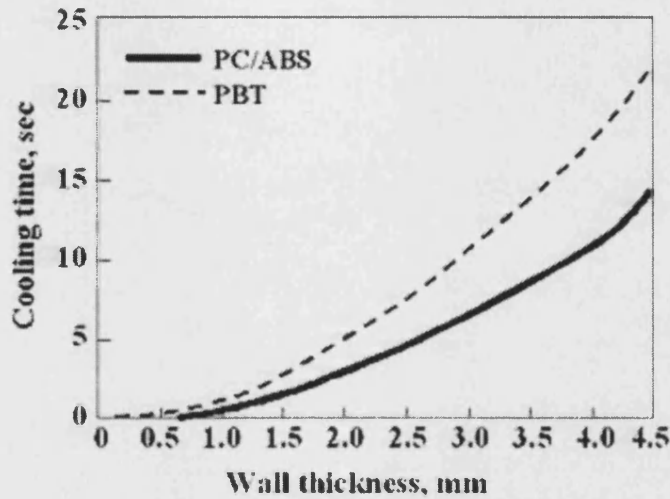


Figure 1.1: The relationship between wall thickness and cooling time for PC/ ABS and PBT material [Douglas, 2001]

Seventeen basic shapes have been identified for injection moulded products. These are described in more detail in chapter 5. In the proposed cost estimating system, a required injection moulded part, during the conceptual design stage, is developed from a series of subparts derived from the basic shapes that are then joined together. Each subpart has a unique shape and has individual definition, volume, dimensions and function. For a maximum wall thickness to be identified automatically, the designer needs to select one of the basic shapes, instead of freeform drawing activities. Then the

dimensions of the selected basic shape should be entered to achieve the required subpart and a wall thickness is specified for each subpart as the result of this activity. When all the subparts have been joined together the maximum wall thickness is calculated using algorithms

The material type and component volume are also important factors in determining the cost of an injection moulded product [Dewhurst, 1988; Kals, 1996; Weustink, 2000]. In addition, it was the author's experience that designers would benefit if they could see the effect of using different material types on the product cost. Hence, a selectable database of material has been developed which, enables the designer to choose a wide variety of injection moulding materials during the conceptual design process.

Visual FoxPro 7.0 programming software [MSDN, 2001] has been used to develop the material database and also to develop a new program for concurrent cost estimation within the Ideas software package. The developed FoxPro cost estimation program links the Ideas output files with the material database and uses a series of parametric equations to estimate the cost. The rules of this work and the proposed methodology for determining the conceptual cost estimation are the key aims of this research work.

1.6 Conclusion

It is commonly agreed that a large proportion of the final product cost is determined and locked in at the product design stage. It is thus valuable, to spend time and effort at the design stage in order to reduce the final product cost. However, it is difficult to design a cost-effective product unless the critical cost factors are identified and considered at the conceptual design stage. An effective means of encouraging the designer, who may not be familiar with the manufacturing process to be used, is to provide concurrent cost estimates at the conceptual stage of design, where design alternatives can be considered.

To achieve this, it is necessary for the costs to be modelled and represented at the conceptual design stage. Most of the research work in this area has estimated costs at the conceptual design stage using either mathematical, parametrical modelling or empirical formulas as the primary tools of cost estimation. However no published work could be found in the literature that described a concurrent cost estimating system for injection moulded products at the conceptual stage of design. This research study attempts to overcome this shortcoming by developing a system for injection moulded products, which enables product cost to be estimated throughout the conceptual design stage. This system has also been developed with a significant level of automation and is displayed concurrently by linking the design activity with conceptual product knowledge.

Chapter 2

Literature Review

2.1 Introduction

As described in chapter 1, the conceptual stage of design is the most critical stage in defining the final product cost. It was also suggested that an accurate cost estimation at this stage was critical to the design process.

In order to identify the various conceptual costs estimating methods, which have been documented, a literature review was carried out to identify any relevant material on the subject. There has been much work by researchers and industrial groups, in the area of conceptual cost estimation. In this chapter, the methods that have been put forward are classified based on the type of methodology that has been used by the researchers. The cost estimating methodology of each category is described and the problems and advantages of each method are discussed. Most importantly each method is evaluated with regard to its general applicability and use in a concept design stage cost estimating system.

2.2 Cost Estimating Methods

Several different methods of cost estimation were found to be in use at the present time. These methods are currently applied to a wide variety of engineering components at various stages of product design. The more important of these methods are detailed in the following sections.

2.2.1 Decision tables

A decision table is a symbolic way of representing the logical interdependence between events in a simple tabular form. A set of tables can be established that link product attributes to relevant costs and once constructed, they can be used for cost estimating.

Chin and Wong [1996] described a knowledge-based costing system for an electrical appliance manufacturer to assist mould cost estimation at the conceptual stage of design. In their system through the use of decision tables, numerous interrelated variables and technical data in the injection mould cost estimation process are organised and presented. Qiang [1991] developed a computerised cost model using decision tables for advising on plastic material selection and developing good “design for manufacture” practise in mould design.

The decision table method is easy to understand and use but it requires a significant amount of expert knowledge to be elicited prior to the tables being set up. It is thus a process specific method. The accuracy of the method is highly dependent on the quality of the expert knowledge

2.2.2 Fuzzy sets

In the cost estimation process, there are known physical/engineering variables with definite values and there are probabilistic/random variables, such as labour fatigue rates, resource shortages, machine failure, etc. which cannot be accurately predicted. This uncertainty can be incorporated into a cost estimating system by using fuzzy sets that have both deterministic and probabilistic variables as inputs. The cost estimation

can then be obtained from the fuzzy set output variables. Several examples of the use of this technique have been documented.

Shirley [2001] developed a fuzzy logic cost estimation method for high production volume components. This method, the cost of the component is estimated based on the components geometric shape, size, material and manufacturing process. Musilek [2000] developed a method to estimate the cost of new software development. In this method the software size can be regarded as a fuzzy set yielding the software cost estimate. Wiehn [1996] applied the fuzzy concept for cost modelling of waste in incineration plants. Edwards and Petley [1997] introduce capital cost estimation by applying fuzzy matching Whilst Jahan-shahi [1999] developed a fuzzy model for cost estimation of a flat plate process. In their model a job order must be broken down into different activities with each activity in turn being broken down into several cost elements. The rationale behind the system is the fact that total cost is equal to the sum of the cost of all individual activities and the cost of each activity is equal to a known activity rate multiplied by a corresponding variable activity time. Therefore to provide an accurate cost estimate, the estimator must generate reliable time estimates for all activities.

Almost all known cost factors can thus be included in the fuzzy sets and this is considered to be an advantage, but since the cost estimation involves uncertainty, it is necessary to output a range of possible costs. If the process specific input information can be obtained, and this again is considered difficult, then it is claimed to produce a reliable cost estimate.

2.2.3 Time scale

Processing and assembly times themselves give a good indication of the product cost and these have been used to assist the designer to estimate costs at the design stage. To do this the hourly production rates for equipment and labour are derived and then built into semi-parametric equations. Schreve [1999] described a model that is aimed at estimating the manufacturing time of fabricated steel assemblies that are to be manufactured in a batch production system. Similar models also have been proposed by Schreve for sawing, guillotine cutting, flame profile cutting, rolling, bending and welding [Schreve, 1998; Maree, 1997; Schuster, 1997] presented similar models for estimating the cost of fabricating products in a jobbing prototype shop. Models for drilling, punching and machining operations have also been described by Boothroyd [1994].

Time scale models are considered to be applicable to very simple situations for which it is fast and reliable. However its application is limited, the process specific information is difficult to obtain at the conceptual design stage and it is thus more applicable to the latter stages of design.

2.2.4 Activity Based Cost (ABC)

In the activity-based cost estimating method, the main input for cost estimating is the consumption of resource. For this method the primary design attributes and support related attributes that affect the final cost of the product are used to derive cost estimating equations.

This method has been used by many organisations for product costing and to manage resource consumption and monitor activity performance. Kaplan and Cooper [Kaplan 1999, Cooper 1988] have used the ABC system to estimate the cost of surface machining a product. Ullrich and Fine [1990] proposed using ABC as a cost model in process-driven product design. Tsai [1996] developed an activity based costing method for media and entertainment products, to improve the accuracy of product cost data derived from the traditional cost system. A concept for establishing viable ABC models that can aid cost estimation during the early stage of designing products and systems has been proposed by Lee and Kim [1998].

Generally, in the ABC method a semi parametric approach is used. Although relevant historical cost data was available for Lee's research using this method, it was still necessary for an extensive study of the primary design attributes to be carried out. It is claimed to be a general solution that produces a reliable estimate.

2.2.5 Bottom-up

The bottom-up approach is similar to the time scale approach. The times needed to produce each part are calculated along with the hourly rates for machinery and labour. The times and rates are then multiplied to get the processing costs. To estimate the product cost, indirect and overhead costs are then added.

Several examples of the use of this technique have been documented. Blecker and Smithson [1985] developed a computerised bottom-up cost estimating system that builds up a comprehensive cost estimate by modelling the direct, indirect and overhead costs. Pugh and Mahmoud [1982] developed a costing system for turned components. Their

system used both manufacturing time and material costs to estimate the product cost. In the model proposed by Hancock [1994] the costs are divided into fixed costs, variable costs and tooling costs. The fixed cost are sub-divided into three areas namely: machine hour rate; run-length factor and other factors. Variable costs are described as; raw material costs, bought out parts; electricity costs and transport costs. For tooling costs, Hancock states that most estimates can only be based on a firm tool quotation obtained from tool-makers once the component drawings have been studied and the type of tooling required discussed.

The main advantage of a bottom-up cost estimating approach is its flexibility and its accuracy [Currie 1996]. The information used in the formation of the estimate is based on and can be applied to numerous different products. Although this was put forward as a "design stage" method it is not considered to be applicable for early cost estimating as it requires considerable design detail to function.

2.2.6 Feature based costing

In many cases, the product geometry directly affects product costs, and can be considered as a cost driver for cost estimating. If the features that affect product cost can be identified at the early design stage they can be used, via equations, as the basis of a cost estimating method.

Poli [1990] describe how costs can be trimmed by using a systematic method to rate design, based on certain casting parameters such as design features and casting size. Bidanda [1998] developed an intelligent castability and cost estimation system using geometric parameters of a component such as part shape, size, and complexity that

influence the cost of the part. An integrated framework for feature based early manufacturing cost estimation has been developed by Yang and Lin [1997]. Their system estimates the manufacturing cost of a design, according to the shapes and precision of its features. The aim of their system is to provide a tool to assist the designer, who has little knowledge of the manufacturing process, to be used to estimate the fabrication cost of a design during its conceptual stage.

The feasibility of developing a feature based complexity factor for costing of items at the conceptual stage of design has been examined by Dunleavy [1991]. Features in relation to component composition are described by [Chang 1990] where he used binary trees to represent the construction of a component using basic essential shapes or features such as block, cylinder, wedge, sphere, cone and torus.

The feature based costing method is generic and flexible but process specific information is required that is experienced based and the quality of this information can significantly affect the accuracy of the estimate.

2.2.7 Parametric method

Parametric cost estimating systems utilise the empirical relationships between cost parameters and selected physical properties or performance parameters of the product. The parametric method reflects these relationships in the form of mathematical equations, which can then be used to estimate product cost.

Mileham [1992] has developed several parametric methods in different aspects to estimate the cost of the product at the conceptual stage of design. In his methods the parametric equations are derived from a large database of component information using

multiple linear regression analysis. A computer-based cost estimating system for a range of injection moulding product has been investigated by Currie [1996]. His model is capable of estimating costs to within $\pm 20\%$ and is suitable as a base for the development of a conceptual cost comparison system. Several cost estimating methods for composite material applications were investigated by Zallom and Miller [1982]. Their models consist of a set of parametric equations for each level of detail available to the estimators whilst, Eversheim and Rothenbucher [1985] outline the following guidelines for the arrangement of a parametric cost function:

- 1- Consider a large group of products.
- 2- Search for potential variables of influence, i. e. cost drivers.
- 3- Plot the product costs against each variable and check that the potential influence is real by applying regression analysis.
- 4- Show the costs as a function of the relevant variables.
- 5- Evaluate the accuracy of the function by comparing its outcome to the costs of existing products.

Over and above the research published in the academic literature there are several parametric cost estimating packages which are commercially available, for example:

ACCEM(Advanced Composites Cost Estimating Models) [Northrop Corporation,1976]

STEP(Structural Technology Evaluation Program) [Kenneth , 1998]

This highlights that this is one method that is used in a commercial setting and available for purchase. Generally, for the parametric approach minimum component information and little or no experience of the process to be used to drive a cost estimate are the main advantages but identifying the equations requires experience and significant amounts of historical cost data.

2.2.8 Group technology

The group technology method is based on the principle of product similarity and uses a family cost value that is modified by the actual components real size, complexity, etc. A part coding system is used to assign a unique code to a part based on various features of the part.

A method to estimate injection mould tooling cost using a six-digit code of a part design has been described by Poli et al. [1988]. Look-up tables were used to extract the cost driver based on the code. In their method simple linear relationships were used to link the final cost and the variable cost factors. Aside from the real use of group technology there has been very little work on product cost estimation using group technology. The method is easy to use if a group technology system is in use.

2.2.9 Cost estimation by comparison

Comparing a new product with similar existing products can be the basis for a cost estimate of the new products. The comparison can be based on product features, complexity, shape, weight or the method of manufacture. Allowances can be made to account for any difference between new and existing products.

A comparison cost estimation system has been investigated by Brinke [Brinke, et al 2001]. In his method it is assumed that geometrically similar products are manufactured with the same production process. The cost of the historical products that are similar to a certain degree can be used to generate a cost estimate i.e. the average cost of these products. It is claimed that this method is quick and very useful in the early stage of product design. Meisl [1988] method, which used the preliminary STS Orbiter development costs was achieved using historical cost data for other programs, which were broken down into major sub-systems. These sub-systems were then adjusted for complexity so that they could be used for the cost estimating of new programs.

A computer-based method for the cost estimation of injection moulded products is described by Welch and Lobe [1984]. Their system used component classification to assign mouldings to one or more specialised tool groups. Each group is defined as tool and component characteristics, and variables, which reflect the significant tool cost parameters are then used to encode the component. This information is stored on a database file and is used to automatically recall all of the previous jobs with similar characteristics, these being ranked according to similarity. Predicate equations are then used to calculate the mould manufacturing time. If any special factors exist, such as high performance or economy features then the estimator can adjust for these as necessary. Each component for which the cost is being estimated is ordered and the database is then up dated with the data arising from the ordered components.

The main factor in using the comparison cost estimation method is the need for a relevant historical database of products or similar features or manufacturing methods. In

this case a fast cost estimate is the result but accuracy bears a significant relationship to product similarity.

2.2.10 Neural networks

The cost of a new product can be estimated using neural networks in two stages. In the first stage a knowledge base of existing products and their historical cost is built up. In the second stage, the cost of the new product is estimated by comparing the new design specification with the knowledge base information.

Shtub and Versano [1999] developed a cost estimation model for steel pipe bending using neural networks that can be linked to CAD data. The CAD output data was used as input data to the cost estimation model. Their system learns how to modify cost estimates when a new technology is developed. Zhang and Fuh [1998] describe a feature-based cost estimation method using a back-propagation neural network to estimate the cost of packaging products at the early stage of design. Their method consists of two stages namely the preparatory stage and production stage. At the preparatory stage the construct and training of the neural network is developed using existing products and their historical cost data. During this stage, the domain of the product spectrum is defined with all the cost-related features of the product being identified and quantified according to their influence on the final cost. Next, existing products are coded to form the cost related feature matrices. A back-propagation neural network is then constructed and the information is stored in a knowledge base to use at the production stage. At the production stage a new product is first coded to obtain its

cost-related feature matrix according to its design specification. The matrix is then entered into the network to estimate the cost of the new product.

Neural networks have also been used to estimate the cost of assembly systems [Shtub and Zimmerman 1993]. They emphasise the comparison of performance between the neural network model and the regression model.

An advantage of neural networks is that virtually all cost aspects can be incorporated but as with most other methods, the accuracy is dependent on the availability of good historical cost data.

2.2.11 Subjective approach

The subjective approach is based solely on the experience of designers and their familiarity with the part being designed [Miranda, 2000]. Cost estimates do not come from collected data from past similar work or by other departments. Cost judgment is based entirely on the designer's sense of perception and his/her expertise. Although there is not any published method using the subjective approach for cost estimation, the cost of many new software packages is estimated by the subjective method [Lionel et al, 2000].

2.2.12 Expert systems

An expert system, in the form of either a computer program or a narrative procedure contains a domain specific knowledge base and a set of rules [Chin and Wong 1995]. The expert system can be used to generate a cost estimate from product input data

which chains through the rules until a conclusion is reached. In recent year's expert systems have been successfully applied to the cost-estimating problem.

Bock [Bock 1991] describes an expert system, which consists of four basic modules and is used for materials and process combination selection, including materials knowledge, a knowledge acquisition mechanism, design analysis and cost estimation. Shetty and Napolitano [1990] described an expert system for material selection to satisfy required design and production criteria. Nagarajan [1996] described a computer aided cost estimation system for ball grid array (BGA) and direct chip attach (DCA) technologies. The aim of such a system was to help an informed user to compare the cost of assembling a printed circuit board with traditional peripherally leaded devices against functionally comparable BGA and DCA devices. The customer order relaying assistant (CORA) expert system assesses electrical relay type and style number and uses a hierarchically organised inheritance function to provide bills of material and quotations [Welsh 1988]. Expert systems have also been used to predict cost-time profiles for certain activities in the construction industry [Christian 1991].

Expert cost knowledge can be obtained from a variety of sources but it is difficult to elicit accurately and to generate rules from it. Such systems are process specific but can be used by non-experts to produce early estimates with reasonable accuracy.

2.3 Overview of the research problem

Several methods have been discussed relating to cost estimating at the early stage of design. The majority are process specific and require considerable amounts of cost, process and product information and time to set up. Although researchers claim that the

methods are generic and thus capable of expansion, none of the methods reviewed have in fact been expanded because of the difficulties involved. None of the methods reviewed contain both a high level rough cut estimate and a lower level process specific estimate, although this would have considerable advantage for cross process comparisons at the early design stage.

Obviously, one particular cost estimation technique could not be applicable for all manufacturing processes. Each cost estimation technique has its own capability, reliability and accuracy. There is no reason to think that one method is more applicable and accurate than another. This is because a model typically consists of a simple formula and constants and should be easy to understand and use, provided the engineer has at least an elementary knowledge of the capabilities and limitations of the processes under consideration. It should also be possible to add an advisory system to assist the inexperienced designer in finding candidate processes, to the computer implementation of the cost model.

Table 2.1 shows a comparative table of existing cost estimating methodologies that have been used by researchers. This comparison has been undertaken to compare the benefits and the limitation of developed cost estimating methods. The parametric method is good to use when limited component information is available. The comparison method is applicable when similar products exist and historical information is available for existing products. The conceptual design stage does not yield enough information for bottom-up cost estimating. The time scale approach is suitable when the product characteristic variables affect the final cost and are related to the time scale variables. The subjective approach is easy and fast but estimation of the cost is dependent on the experience of the

designers. This method is not a feasible cost estimation technique for a designer who is not familiar with the manufacturing process to be used. The group technology approach should be useful in factories having a GT layout but it is not generally applicable.

Furthermore, because of the limitations of the current cost estimation methods, the requirements of the conceptual stage of design leads to only a few cost-estimating methods being suitable for this stage.

Although some of the reviewed conceptual cost estimating methods, could be applicable for the conceptual cost estimation of injection moulded products, which is the subject of this research, it was thought that it could be a benefit if a hybrid or a synthesis of current cost estimating systems could be established. This would use the advantages of the existing cost estimating methods to their maximum.

A synthesis of feature based costing, the parametric method and an expert system in the form of a computer program for cost estimation was therefore chosen for the conceptual cost estimating of injection moulded products for this research. Feature based costing was chosen because feature geometry is usually identifiable at the conceptual stage of design. Parametric cost estimating was chosen because it allows an accurate estimate to be made from limited component information. Also the parametric cost estimating equations are typically developed based on the information available at the conceptual stage of design. The expert system in the form of computer program was chosen to use the benefit of computers in cost estimation. The benefits are described in chapter 4.

2.4 Research Aims and Objectives

The aim of this work is to develop a conceptual cost estimating system that is integrated with a CAD package, is automated and allows an on-screen cost estimate to be shown as the product is constructed. In its research form it is limited to the cost estimation of injection moulded products. The research has the following objectives:

1. To carry out concept design and concept stage cost estimating concurrently.
2. To reduce the time and effort of cost estimation.
3. To create a cost information database.
4. To improve the design phase cost documentation.
5. To increase the visibility of cost and features relationship.
6. To improve the designers productivity by reducing/eliminating manual searching of cost data files.
7. To increase cost estimation reliability by eliminating manual errors.
8. To increase cost estimation performance for new designers.

The system is considered to be applicable to a wide range of injection moulded products.

2.5 Research System Limitation

Since the proposed cost estimating system is to be used initially for research purposes, certain boundaries have been placed to limit its scope and logic. These boundaries are:

1. Only the cost of injection moulded products can be estimated using the proposed system.
2. The design process should be started and proceed, using the pre-designed features instead of freeform design.
3. The first two characters of the pre-designed feature's name are important factors for cost estimating. For example the name of a pre-designed solid cylinder is considered to be "P4". These two characters should not be changed during the cost estimating process. Adding to these two characters, however, is possible.
4. The pre-designed features do not included freeform 3-D surfaces.
5. The proposed system of product construction dos not considered the mouldability of the product.
6. The estimated cost dos not included tooling costs.
7. The process of decomposition has been used exclusively to construct products using features.

Table 2.1 Comparative table of cost estimating methods.

	Method	Where Used	Advantages	Limitations	Accuracy
1	Decision tables	Injection mould company	Using technical data, easy to understand and use	Needs expert knowledge and historical data	80%
2	Fuzzy sets	Flat plate processing	Can use almost all the cost influencing factors	Inherently uncertain	Reliable range
3	Time scale	Tack welding, sawing, guillotining	Fast and easy for cost estimating	Could not be use for complex process	Reliable
4	Activity based cost	General	Uses direct and indirect historical cost data	Needs significant historical data to function correctly	Unknown
5	Bottoms-up	Turned component products, machined components	Flexibility, no need for one or more existing products	Need expert and experience to use information correctly	Reliable
6	Feature based costing	Injection moulding	The cost estimation can accommodate shape changes	Results highly dependent upon experience	Reliable
7	Parametric method	Composite materials, Injection moulding	Minimum component information needed, easy to use	Identifying equations that relate features and costs	80%
8	Group technology	Injection moulding	Fast and easy cost estimates	Simple linear relationship between the final cost and the variable cost factors	Low
9	Cost estimation by comparison	STS Orbiter development	Simple cost estimating	New and existing product must be similar. Historical data required	Reliable If data available
10	Neural networks	Packaging products	Looks at overall cost.	Accurate historical data and experience required	Reliable If data available
11	Subjective Method	Software cost estimation	No historical cost information is needed, fast and easy	Cost estimation is directly depend on the designer experience	Unknown
12	Expert system	Printed circuit boards, Casting, Injection moulding	Uses many cost drivers. Fast interactive evaluation,	Takes time to create the system. Derivation of rules difficult	Reliable If data available

Chapter 3

Cost Estimation Methodology

3.1 Introduction

Some of the existing cost estimating methods, that have been described in chapter 2, are able to estimate the product cost during the design phase, but none of them are able to make a concurrent cost estimation and analyse the product cost at the conceptual stage of design. Current methods tend to be applied to choose between design alternatives at the late design stage or to evaluate the product costs. To estimate and analyse the product costs, it is necessary to have knowledge about the cost consequences of decisions during the conceptual stage of product design.

The process of product design consists of a large number of decisions being made such as product dimensions, features, raw materials, surfaces roughness, tolerances, selection of production methods, etc., that have a great effect on the products final cost. To be able to estimate the product costs adequately, it is necessary to indicate the product cost drivers such as weight and material price and their consequence on the product cost. To ensure this is possible, cost data needs to be stored, to offer a consistent analysis. One solution to this is to use a concurrent cost estimation approach, which enables designers to have an idea of the product cost, when they are developing a new product design. This chapter describes the authors proposed method of cost estimation, which in his view meets these requirements. Figure 3.1 presents a flowchart diagram of the proposed methodology for concurrent cost estimation.

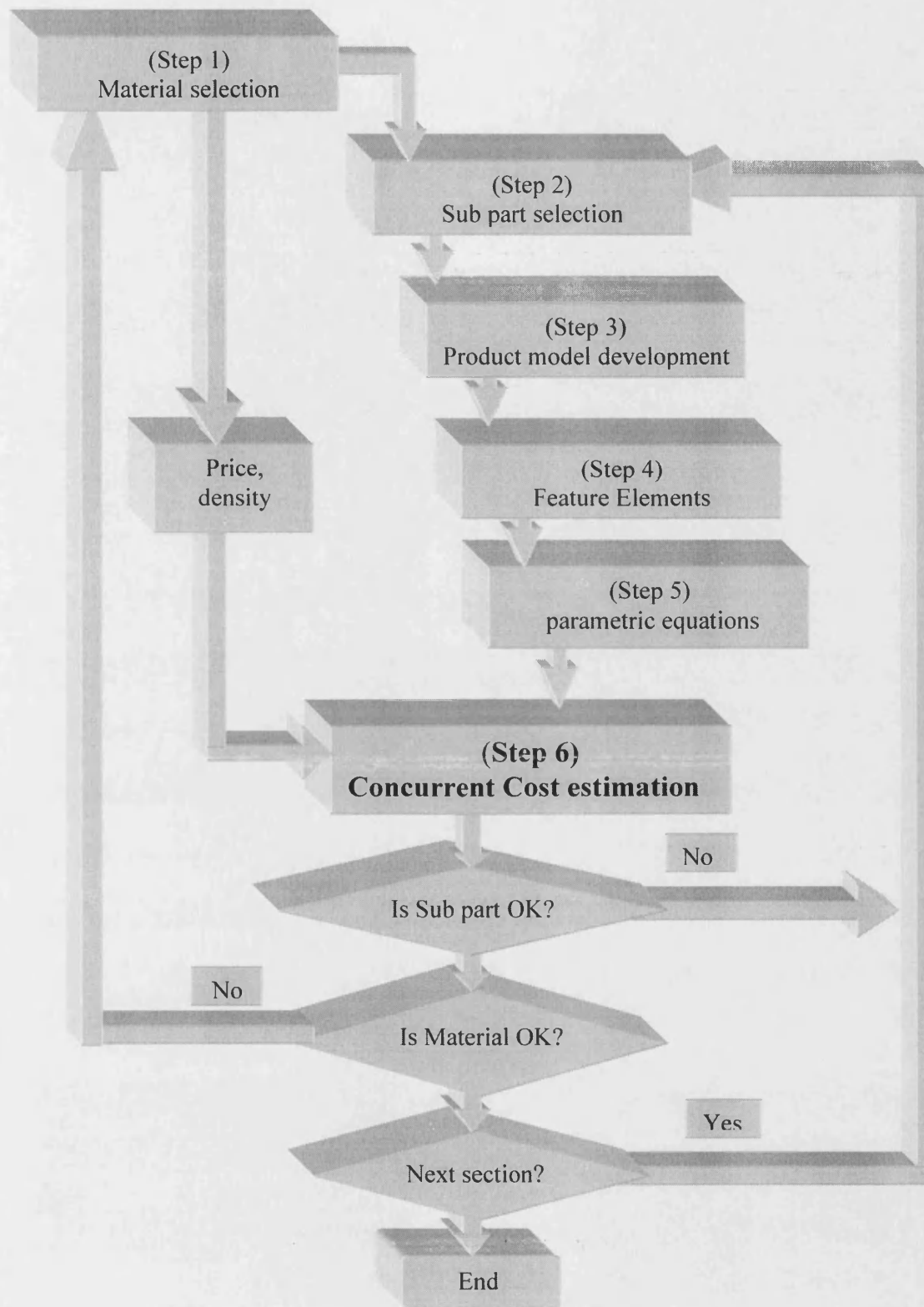


Figure 3.1: Proposed conceptual cost estimation methodology

The proposed methodology has six major steps. The objectives of each step are described as follows;

3.2 Step 1-Material selection

Material selection is one of the most important factors in the part design process [Dieter, 1988; Robert, 2001]. The selection of material for a component is not an easy process but it is primarily dependent on the physical and mechanical properties required. In actual practice, most of the following material properties are considered: strength, hardness, thermal conductivity, stiffness, density, melting temperature, price, etc. In most cases, these material properties would influence directly, the machine, mould, cooling time and some other production factors that could affect the products final cost. This research uses a few injection moulding materials to verify the research work. The material information was gained from the latest information of injection moulding material on the world wide web (WWW). This material information can be changed or updated when needed. For the research this information is used to provide an editable and selectable computer database of injection moulding materials. This enables designers to choose the best possible injection moulding material, before and during the design process. This database consists of the material name, characteristics, type, density, price, scrap rate, dry-time, thermal time, lower thermal time and upper thermal time.

3.3 Step 2- Sub-part Selection

Step 2 uses a series of three-dimensional generic features to form the basic shapes for injection moulding product development (Figure 3.2). These potentially generic features were identified by examining existing products and then incorporated Ideas design software. They can then be used as basic shapes, to design a wide variety of the sub-parts required for product development. The generic features are assumed to be used by Ideas users; other designers however, can use them in a neutral format.

Two different types of basic shapes have been developed for the creation of injection moulded sub-parts. The first types have been developed using a set of standard shapes such as circles, triangles and squares. Combinations of the same standard shapes such as two squares, three squares and, synthesis of different standard shapes such as circles and triangles, are used for creating the second set of basic shapes.

Dimensioning is an important factor in creating the basic shapes. An excess dimension prevents the basic shapes modification (Figure 3.3) and some unnecessary dimension may destroy the basic shape wire frame (Figure 3.4). To be able to cover a wide range of injection moulded products with the smallest number of basic shapes, special dimensioning has been applied to the basic shapes. Changing these dimensions enable designers to design a wide variety of injection moulded components. In addition these specified dimensions are used for calculating of the maximum thickness of the sub-parts and developed products. This is one of the main aims of this research leading to concurrent cost estimation. The proposed basic shapes and the applied dimensions are discussed in greater detail in chapter 5.

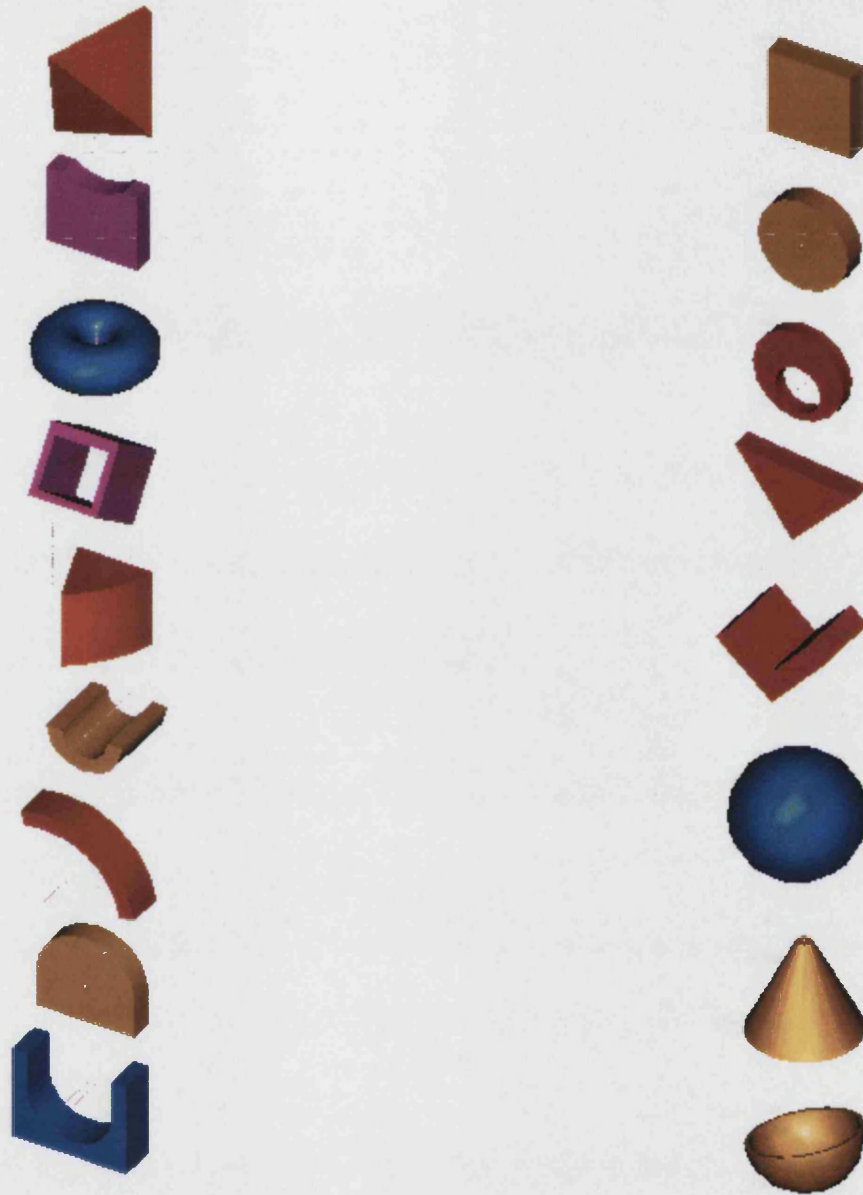


Figure 3.2: Proposed Generic Features of injection moulding products

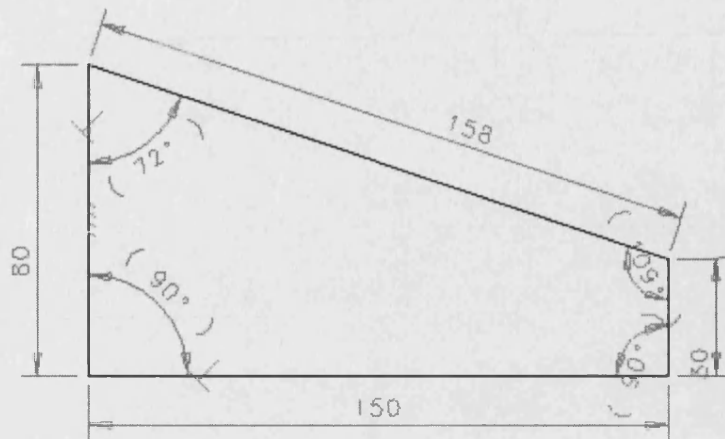


Figure 3.3: A basic shape with excess dimensioning

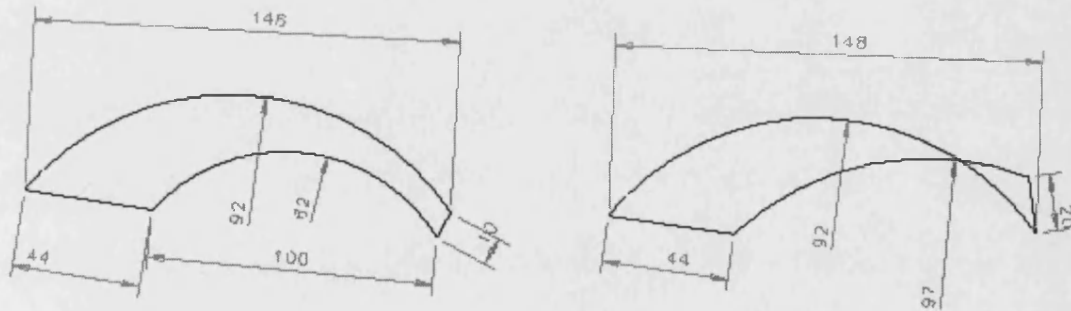


Figure 3.4: A basic shape with unsuitable dimensioning

3.4 Step 3- Product development

At the third step, a new build up process is proposed for injection moulded components using the three-dimensional basic shapes. The main aim of this step is to establish a method for an injection moulding product design process that helps conceptual cost estimations to be made. The application of basic shapes for product development arise from the reality that, a product can be represented by means of elements and relationships among elements. This reality is more obvious in mechanical assembly systems.

Figure 3.5 shows an injection moulded component, constructed by sub-parts, that has been developed from three-dimensional basic shapes. This approach has three main advantages:

The first advantage is that generic features usually provide a natural vocabulary to capture the design intent, provide a basis for modelling various manufacturing information and facilitate the management of parameter relationship and dependencies. In addition, through using generic features the process of system standardisation can be possible. The second advantage is that, using generic features will decrease the design process activities. The designers usually start the process of product design using two-dimensional basic shapes such as circles, triangles and squares. Two-dimensional basic shapes are then changed into three-dimensional wire-frame or solid shapes. Other changes such as holes, slots and cuts are applied later. For example, to design a simple cube, designers need to draw a rectangle and add dimensions. Then, they need to extrude it to make a three-dimensional solid cube. Using a pre-designed cube, eliminates the necessary activity of drawing the rectangle and extruding it to a cube. In other words, the

required activity is limited to changing the pre-designed cube dimensions. Also, pre-designed three-dimensional features are much more visible during the design process, this is more desirable for new designers.

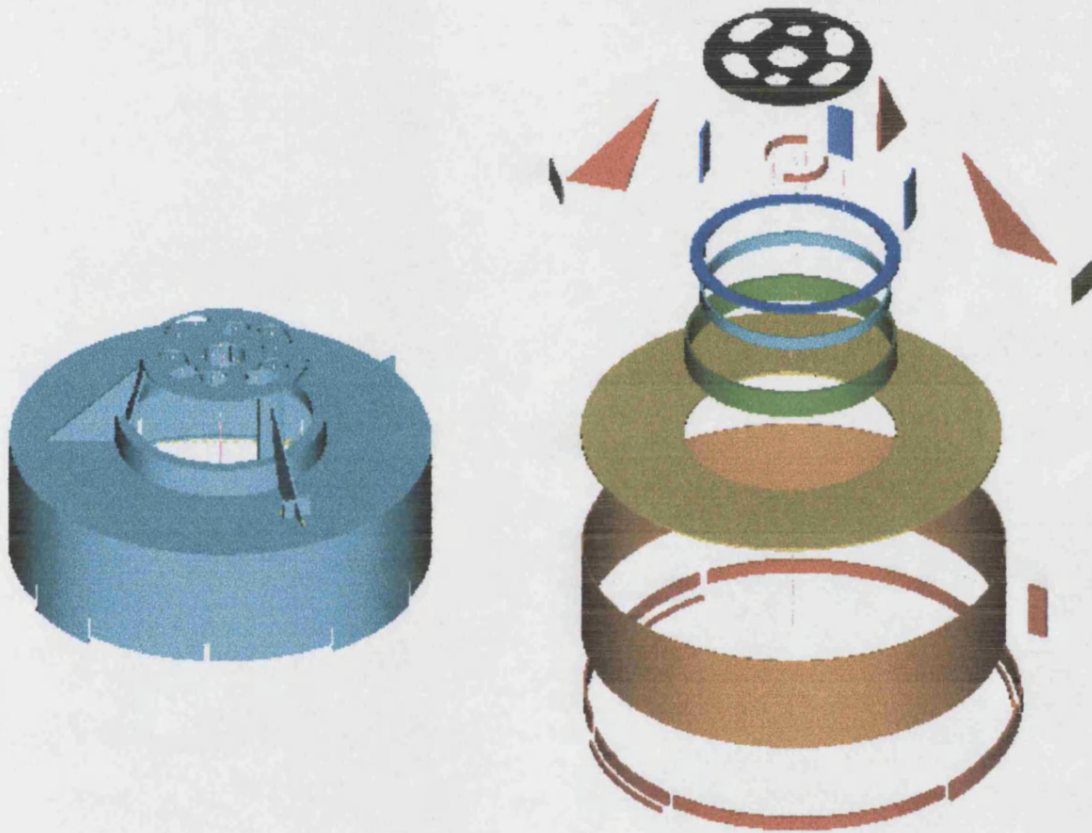


Figure 3.5: Developing injection moulded component using sub-parts

The third advantage is through using generic features for product development, the minimum dimension of each sub-part can be gained. This minimum is supposed to be the maximum thickness of the sub-part, and can be used for the sub-part cost

estimation. In addition, the minimum dimension could be used for the calculation of the maximum thickness of the developed injection moulded component.

3.5 Step 4- Feature elements

At the fourth step, the effects of each sub-part on the product cost are analysed. Each sub-part could affect the product cost in three ways: adding product volume, changing product maximum wall thickness and adding product complexity. Product volume has a direct effect on the product weight and cost and needs to be calculated accurately. Depending on the shape of the sub-part, the calculation of product volume could be difficult. The Ideas design software, is able to calculate the product volume. The author used this output and applied rules to develop new software that enables designers to use directly, the sub-part volume that is output using the Ideas software. Ideas is used to illustrate the methodology proposed by the author. The software and the rules for the process of volume transformation are detailed in chapter 6.

Maximum wall thickness has a direct effect on the product cooling time that could change the product final cost. As it is stated in 3.4, minimum dimension of each sub-part could be the maximum wall thickness of the sub-part, but this maximum may change during product development. The maximum wall thickness of combined sub-parts could be the maximum radius of the joined section. The maximum radius of the sub-parts and the maximum radius of joined sub-parts can be calculated by using the series of mathematical equations provided in section 6.2.2.2. This research provides a

means of offering a concurrent product maximum thickness that can be used for cost estimating process during the conceptual stage of design.

Product complexity has a major effect on its costs. Factors of complexity for injection moulding product can be divided into two main categories: the first category involves the factors that can influence the mould opening direction, mould parts and mould parting lines. Examples of this category include internal threads, cross-holes, and undercuts. The second category covers factors such as tight tolerance and gloss surface finish, which can have an effect on the material and mould temperature. Both of these elements are considered for the cost estimation process and are discussed in chapters 6 and 7.

3.6 Step 5- Parametric Equations

Step 5 uses, a series of parametric equation to estimate the sub-part cost. These equations were developed in a research program [Currie, 1996] of conceptual cost estimating at the University of Bath. The equations derived from a large database of component information are able to estimate the cost of injection moulded products within the desired $\pm 20\%$ accuracy. These equations are used because they have been developed to create conceptual cost estimates for injection moulded products with minimal information. These equations are based on the product weight; production volume, cycle time and machine hourly rate and are able to estimate the product cost at the conceptual stage of design. The parametric equations have the following restrictions;

- 1 - The component are moulded using hot runners data for runners and sprues has have been excluded.
- 2 - Secondary operations such as packaging, plating etc. have not been included.

3 - Special injection moulding techniques such as Double Screw Machines, Two Colours injection, etc. have not been catered for.

The following sections provide details of these equations and their characteristics.

3.6.1 Weight Based parametric equations

Component weight is an important factor for the calculation of the material cost. The material cost usually influences directly overall product cost and can be a cost driver to develop parametric cost equations. The effect of the product weight on the product cost may not be the same for all products. To increase the accuracy of the estimated cost, using weight based equations, it is necessary to categorise products into different weight ranges. The following equations were developed for injection moulded products based on weight ranges lower than 10g, 10g-60g, 60-500g and over 500g.

$$\text{EstCost1 (0-10g)} = (W * P (1 + S)) + (-0.00172W + 0.04217) \quad \text{Equation 3.1}$$

$$\text{EstCost1 (10-60g)} = (W * P (1 + S)) + (0.00041W + 0.05358) \quad \text{Equation 3.2}$$

$$\text{EstCost1 (60-500g)} = (W * P (1 + S)) + (0.00058W + 0.12140) \quad \text{Equation 3.3}$$

$$\text{EstCost1 (>500g)} = (W * P (1 + S)) \quad \text{Equation 3.4}$$

Where W = Component Weight (g)

P = Material Price (£/g)

S = Scrap Rate (%)

3.6.2 Production Volume Based parametric equations

The cost of the necessary tools for making an injection moulded product, usually influences its cost. This cost is dependent on the product that the tool is designed for. In other words an increase on the product volume could decrease the cost of an individual product.

The following two equations were developed based on production volumes up to or greater than 9000 per year.

$$\text{EstCost2 (0-9000)} = \text{EstCost1} \cdot 0.95215 + \text{Ln V} \cdot (-0.0174) + 0.14927 \quad \text{Equation 3.5}$$

$$\text{EstCost2 (>9000)} = \text{EstCost1} \quad \text{Equation 3.6}$$

Where V = Production Volume (Per annum)

3.6.3 Cycle time based parametric equations

The time taken to manufacture the product could be an important factor for many manufacturing companies. However it has little direct influence upon product cost. To develop time-based equations, injection moulding products have been ranged according the product weight and the production volume. The following equations have been derived:

$$\text{EstCost3 (0-60g)} = \text{EstCost2} \cdot 0.83410 + \text{C/N} \cdot 0.002061366 - 0.01335 \quad \text{Equation 3.7}$$

$$\text{EstCost3 (60-300g)} = \text{EstCost2} \cdot 1.08747 + \text{C/N} \cdot 0.001306972 - 0.08649 \quad \text{Equation 3.8}$$

$$\text{EstCost3 (>300g)} = \text{EstCost2} \quad \text{Equation 3.9}$$

Where C = Cycle Time (sec)

N = Number of Mould Impressions

3.6.4 Machine Hourly Rate Based parametric equations

Based on the component weight, cycle time and product volume the following equations are derived for machine hourly rate:

$$\text{EstCost4 (0-30g)} = \text{EstCost3} \quad \text{Equation 3.10}$$

$$\text{EstCost4 (30-100g)} = \text{EstCost3} * 1.60939 + (C * M / 3600) * (-0.075938) + 0.05518158 \quad \text{Equation 3.11}$$

$$\text{EstCost4 (100-500g)} = \text{EstCost3} \quad \text{Equation 3.12}$$

Where M = Machine Hourly Rate

These equations are used within the author's research for the concurrent cost estimation. They have been proven to work as discussed in Currie [1996] and provide a good starting point for proving that the methodology proposed by the author is applicable. The equations are inbuilt into the author's rules within the FoxPro software for estimating the costs concurrently and can be updated when needed. The information necessary for the application of these parametric equations will be completed when the sub-part volume and thickness are transferred into the cost estimating software written in FoxPro.

3.7 Step 6- Concurrent cost estimation

At step 6, a concurrent cost estimation is performed simultaneously with the product development. In the proposed methodology, the first chosen sub-part is proposed as a base for product development. The first sub-part can be any of the necessary sub-parts that are needed for product completion, but the biggest sub-part is preferred to be the first sub-part for the following reasons:

- 1- The designer normally starts with the largest sub-part when designing a part.
- 2- The biggest sub-part can be a base for part expansion like an assembly system.
- 3- The biggest sub-part is very often a base for die making. Secondary sub-parts are then added.
- 4- The biggest sub-part usually needs the biggest amount of raw material and thus incurs a large cost.

An estimated cost of the first sub-part can be used as the base cost for the product cost estimation. After the first sub-part is selected by the designer and its dimensions changed to the required dimensions, the sub-part thickness and volume can be calculated and the first cost estimation can be made. This estimated cost is assumed to be the base cost for product development. As product model development proceeds, the cost of other sub-parts and additional costs of the joining process and increasing complexity will be added to the base cost. The rules to estimate the cost are inbuilt into a software program, which is transparent to the user. Any changes in the product volume, maximum

thickness and cost can be calculated concurrently and can be displayed on the computer screen. The designers are then able to see and also to document the growth of the cost, step by step, as they make changes to the base part. The changes at this stage could be on the sub-part dimension, used material, adding new features, increasing complexity etc. This concurrent system of cost estimation enables the designer, to see and to change sub-parts, which influence unexpectedly the product cost. As a result, a cost effective design process could be performed. The benefits of such a system are described in chapter 8. After this step, the suitability of the sub-part and the suitability of material need to be assessed. If the sub-part and the material are assumed to be fine for product development, the process will be continued. Otherwise, the selected sub-part, or material will be changed to satisfy the design aims, objectives and expected product cost. To document product history, it has been arranged that all information about product development and the product be stored in FoxPro database files ensuring the information is accessible in the future.

Chapter 4

Design and Conceptual Cost Estimation

4.1 Introduction

Conceptual cost estimation plays an important role in product development. For instance, a proper conceptual cost estimation can help the designer to make good decisions regarding the product structure, material and manufacturing process. Today, the need for a vast variety of products is the cause of using many different types of material and manufacturing processes. There are approximately 100000 different materials available for selection during design [Giachetti, 2001], and usually there is more than one method for fabricating a part. This influences the product cost and conceptual cost estimation process. To estimate the product cost, at the conceptual stage of design, it is necessary to establish a cost-reasoning model for new products. To illustrate such a system, the research described in this thesis limits the manufacturing process to injection moulding. This approach increases the reliability of the model and the accuracy of the estimated cost.

In this chapter, some of the main prerequisite factors for a concurrent method of conceptual cost estimation for injection moulded products are described. The selection of the manufacturing system, material selection and design process are discussed briefly, and the necessary steps for a concurrent cost estimation of injection-moulded products are described.

4.2 Design process

Design as described in chapter 1, is regarded as a set of activities leading from the establishment of a product requirement to the generation of the information necessary for making the product. The design process itself differs widely from industry to industry and needs to be defined properly for each application. One of the formal definitions of design is proposed by Diter [1991] where "*design establishes and defines solutions to and pertinent structure for a problem not solved before, or new solutions to problems which have previously been solved in different ways.*" This approach divides the process of design into six steps:

- 1- Recognition of the need.
- 2- Definition of the problem.
- 3- Synthesis.
- 4- Analysis and optimisation.
- 5- Evaluation.
- 6- Presentation.

Recognition of the need, is being aware of the necessary information about the design requirement and restrictions. Definition of the problem involves a complete specification of the item to be designed. This specification includes physical and functional characteristics, cost, quality, and operating performance [Shigley, 1977]. Synthesis and analysis are closely related and are a highly repetitive part of the design process. Here a part is conceptualised by the designer, subjected to analysis, improved through this

analysis procedure, and redesigned. The process is repeated until the design has been optimised within the constraints. The part is synthesised into the final overall system in a similar repetitive manner. Evaluation is concerned with measuring the design against the specification established in the problem definition step. This evaluation often requires the fabrication and testing of a prototype model to assess operating performance, quality, reliability and other criteria [Cross, 1994]. Presentation of the design involves providing the necessary documentation, drawings, material specifications, assembly lists, and so on. At this stage, the design database must be created.

Pahl and Beitz [1984] propose another popular definition of the design process. In their model four main steps describe the design process:

1 - Clarification of the task.

2 - Conceptual design.

3 - Embodiment design.

4 - Detailed design.

Clarification of the task involves providing information about the design requirements, the constraint, and describing these in a specification [Groover et al. 1984]. Conceptual design involves the creation of the functions to be included in the design, and pointing to and developing proper solutions. In the embodiment design step the conceptual solutions are developed in more detail, problems are resolved and weak aspects are eliminated. In the detailed design step the materials, form of individual components of the design and also dimensional tolerances are specified in detail for subsequent manufacturer.

Another definition for design is described by Ohsuga [1989] and is shown in figure 4.1.

The model contains the following four steps:

- 1- Requirements.
- 2- Conceptual design.
- 3- Preliminary design.
- 4- Detail design.

Ohsuga suggest an iterative model in which a series of models are created using the same development procedure and generalisation. The models are developed through a process of analysis and evaluation leading to modification and refinement of the model. In the conceptual stage of design, after the designer has proposed an experimental solution an evaluation is performed to form a number of viewpoints to establish the fitness of the proposed design in relationship to the given requirements. If the tentative solution is not suitable, then it is modified. The process is repeated again until the design is at a situation that it can be developed more and the preliminary design stage will start. In the preliminary stage, the design is refined, and evaluation and modification repeated again in greater detail. Finally, the detail design phase proceeds in a similar style to complete the definition of the design.

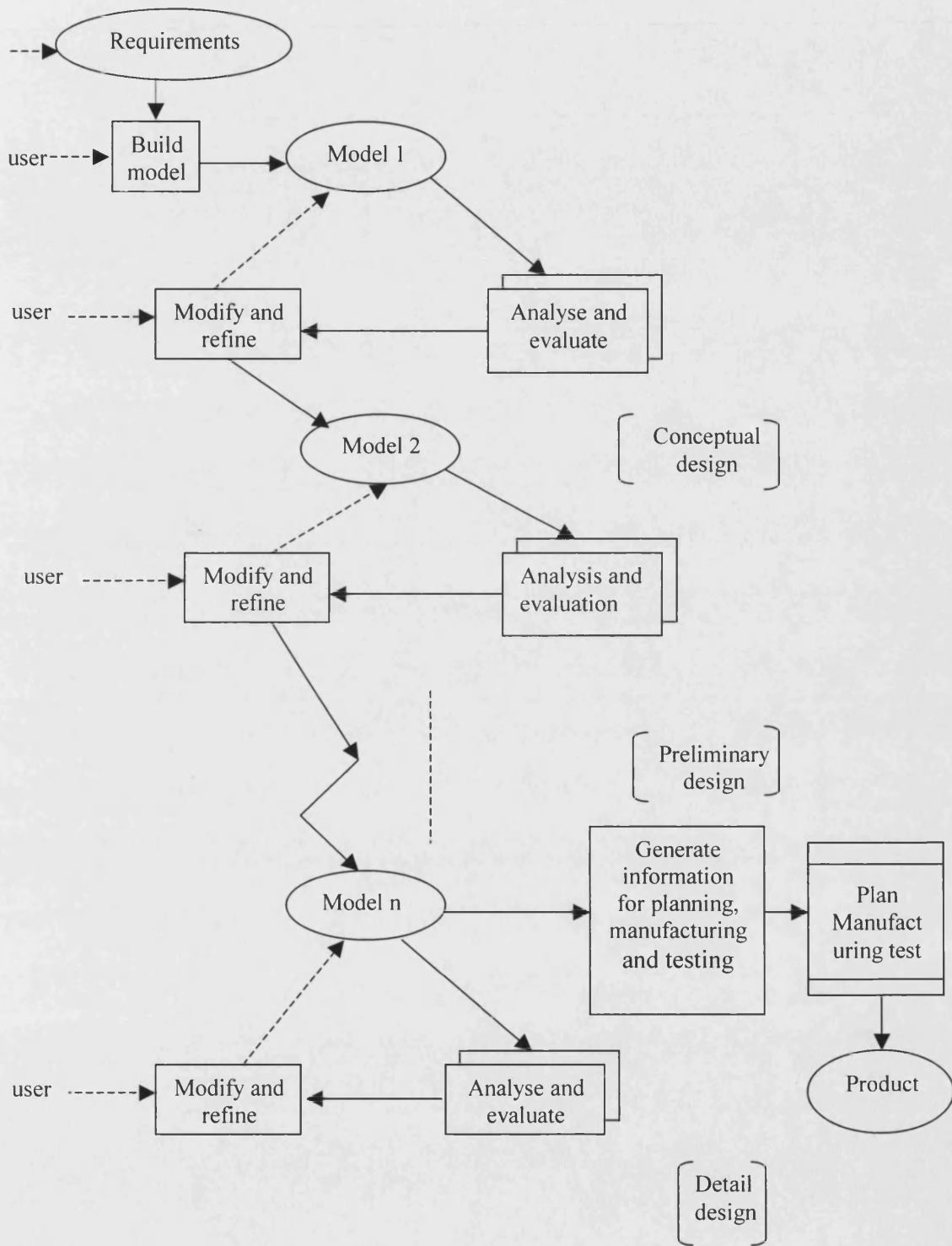


Figure 4.1: The design process according to Ohsuga [Ohsuga 1989].

4.3 Concurrent engineering

Each of the three models described in section 4.2, for the design process, describe a similar process, in which there is a linear sequence of design stages. But today, many companies are under pressure to reduce product design time [Piras 2001, McMahon 1998]. This has led to companies conducting design, analysis, development and the preparation of manufacturing information in parallel or concurrently. In these cases concurrent engineering or simultaneous engineering can be helpful, particularly, for those companies that produce established products, and where new models are required at regular intervals.

Concurrent engineering has been highly regarded as a key concept that enables companies to improve product competitiveness by combining product life cycle into the conceptual stage of design [Sammy, 1996]. These relate to the entire product life cycle from conceptual design through manufacturing to disposal, including product functionality, manufacturability, and cost. However, it is not easy for the designers to identify a design that is functionally acceptable, producible and cost effective at the conceptual design stage, because it involves a multitude of design and manufacturing knowledge. Therefore, it is possible that the manufacturing specialists or design analysts find some aspects of the design need changing, and so the design must be modified or improved. This can occur many times increasing process time and cost. Concurrent engineering is intended to eliminate this by bringing together a design team with the appropriate combination of specialist expertise early in the design process. If there is very high uncertainty in the product development process, or where a very radical design

concept is being developed, concurrent engineering may not be the best approach [McMahon 1998].

4.4 Computer Aided Design

The design is progressively refined, during the design process, until it is completely defined for manufacture. Designers usually construct a series of models of various aspects of the design using a number of representation techniques to assist them in their work. These techniques also support the development, evaluation and extraction of information from the design. Therefore the designer is concerned with a large number and a wide variety of information in the process of design. A major advantage of the use of computers in design is the improvement in information storage and retrieval. In other areas of design, computers facilitate the use of more information and more alternative designs. Computer-aided design (CAD) is one of the areas that the author has identified as being important for more effective cost estimates

Computer-aided design [CAD, 2002] can be defined as the use of computer systems to assist in the creation, modification, analysis, or optimisation of design [Meguid 1987, Linardakis 1996, Rustom 1992, Groover 1984]. CAD is most commonly associated with the use of an interactive computer graphics system referred to as a CAD system. The CAD system consists of the hardware and software, which are effectively integrated into one system to perform the specialised design functions required by a particular user firm. The CAD hardware typically includes the computer, one or more graphics display terminals, keyboards and peripheral equipment. The CAD software consists of the

computer programs to implement computer graphics on the system plus application programs to facilitate the engineering function of the user company.

4.5 CAD Input and output

The purpose of the input/output section of CAD is to provide communication with the variety of peripheral devices used with the computer system. The CAD software can be controlled by user command. The command (programs and data) can be given by keyboard terminals, digitiser, and cursor control. There are various types of output devices used in conjunction with a computer-aided design system. These output devices could be plotters, hard copies, electrostatic plotters, and computer-output in the shape of microfilm, neutral files, animated sequences etc.

4.6 The aim of using CAD

In general, the main aim of CAD is to integrate the engineer and machine in the design process. There are several fundamental reasons for using a computer aided design system. [Linardakis 1996, Krouse 1982] Namely:

1. Increasing designer productivity. Productivity of the designer can be increased through the visualisation of the product and its components, sub-assemblies and related parts and by reducing the time that is necessary for the development of a conceptual design, for analysis, synthesis and documentation.

2. Increasing analytical capability. CAD can enable rigorous product analysis, which would be virtually impossible to perform manually. Also computer-assisted modelling aids such as finite element analysis are usually needed to analyse most structures within reasonable time and cost. Performed manually, the method would be too tedious and time-consuming to be practical.

3. Reducing product and development costs. This is a direct result of increasing engineering productivity and the use of the refined analysis capabilities in the CAD system. In many applications, computer simulation of an entire mechanical system or product is possible. In this manner, functional characteristic such as vibration, noise and stress can be analysed with the computer instead of building costly prototypes. With CAD, computer simulation can be used to determine these characteristics early so components can be designed accordingly. Required changes can be made and the product simulated again until a sufficiently refined design is reached.

4. Creating design document and manufacturing database. In the process of design and providing graphical output through a CAD system, information such as: materials specification, dimensions of the components geometric specification of the product, and so on, can be better documented in a CAD system than manual drafting. A database, which can be useful during the manufacturing process, can also be created.

4.7 Advantages of CAD on the design process

Design is described as the set of activities leading from the establishment of a product requirement to the generation of the information necessary for making the product. What makes CAD technology fundamentally different from others in design, [Pottou 1981] is that it carries through a comprehensive study of a virtual object. The product is or should be conceived, adjusted, and tested without any physical model or prototype being built before the final step. A considerable amount of time is thus clearly saved. Hence quality and reliability are increased and manufacturing costs are reduced. These advantages of CAD systems are considerable and aid this research.

4.8 The CAD functions

Newman and Sproull [Newman and Sproull 1989] list six ground rules that should be considered in designing graphics software:

1. **Simplicity.** The graphics software should be easy to use.
2. **Consistency.** The package should operate in a consistent and predictable way to the user.
3. **Completeness.** There should be no inconvenient omission in the set of graphics functions.
4. **Robustness.** The graphics system should be tolerant of minor instances of misuse by the operator.

5. Performance. Within limitations imposed by the system hardware, the performance should be exploited as much as possible by software. Graphics programs should be efficient and speed of response should be fast and consistent.
6. Economy. Graphics programs should not be so large or expensive as to make their use prohibitive.

Most of today's CAD systems cover all the above ground rules because they are not expensive, they are easy to use and they also consist of sets of functions [CADENCE, 2002, CAD, 2002] and each set accomplishes a certain kind of interaction between the user and the system. Some of the function sets are:

1. Generation of graphic elements.
2. Transformations.
3. Display control .
4. User input functions.

Today's CAD systems are also powerful systems that can work in two and three dimensions. They can create wire-frame geometry such as line and arcs, free-form curves and surfaces and solid modelling. The next sections discuss some of these features in detail.

4.8.1 Generation of graphic elements

A graphic element in computer graphics is a basic image entity such as a point, line, circle and so on. The collection of elements in the system could also include alphanumeric characters and special symbols.

4.8.2 Transformation:

Transformations of graphic elements are used to change the image on the display screen and to reposition the item in the database [Mequina 1996]. Transformations are applied to the graphic elements in order to aid the user in constructing an application model.

4.8.3 Display control

This function set provides the user with the ability to view the image from the desired angle. It makes use of various transformations to display the application model the way the user wants it shown.

4.8.4 User input functions

User input functions constitute a critical set of functions in the graphics package because they permit the operator to enter commands or data to the system. There are a large variety of these input devices in the CAD system that could be very beneficial for users.

4.8.5 Two and three dimension

There are various types of geometric model used in CAD. One classification distinguishes between two-dimensional and three-dimensional models [Jones 1992]. Two-dimensional models are best utilised for design problems in two dimensions Such

as flat objects and layouts of buildings. Three-dimension CAD systems are capable of modelling an object in three dimensions. The operations and transformations on the model are done by the system according to user instructions in three dimensions. This is helpful in the conceptualisation of the object since the true three-dimensional model can be displayed in various views and different angles.

4.8.6 Wire-frame geometry

In the construction of the wire-frame model, the geometry is defined as a series of lines and curves representing the edge of the object [McMahon 1998]. This technique is quite adequate for two-dimensional representation of the object being designed but there are limitations for three dimension objects. The most conspicuous limitation is that all of the lines that define the edges and contoured surfaces and also the lines representing the other side of the object of the model are shown in the image. This can cause the image to be somewhat confusing to the viewer. This interpretation problem can be alleviated to some extent through human intervention in removing the hidden background lines in the image. But even with these improvements, wire-frame models sometimes exhibit certain well-known limitations such as ambiguity, non-completeness or non-uniqueness of the model compared with the object modelled.

Despite these limitations, wire-frame models are used in a wide range of applications [Zhao 1993] because of their simplicity, low requirements of processing time and computer memory.

4.8.7 Surface modelling

Many of limitations and ambiguities of wire-frame models are removed with using the second of the three main 3D-representation [Jones 1992] surface modelling. This represents the model by specifying some or all of the surfaces on the components. It can provide a more detailed description of a parts surface geometry and surface and edges can be defined more accurately. Surface modelling is very useful for curved surfaces in producing smooth continuous surface.

4.8.8 Solid models

The ability of computer-aided design is improved over the wire-frame and surface models by the solid modelling approach [Zimmers 1982, Groover 1984]. In this approach the models are displayed as solid objects to the viewer, with very little risk of misinterpretation. In solid models the image becomes strikingly realistic if different colours are added. The use of solid models can be promoted with two factors [Mantyla 1985]. The first is the increasing awareness among users of the limitations of wire-frame systems and the second is the continuing development of computer hardware and software, which make solid modelling possible. In order to operate a solid model, a great deal of computational power, in terms of both speed and memory is required. To solve the problem two basic approaches have been developed [Mantyla 1996]:

1. Constructive solid geometry (CSG): That allows the user to build the model out of solid graphic primitives, such as rectangular blocks cubes, spheres, cylinders, and pyramids.

2. Boundary representation (B-rep): That allows the user to draw the outline or boundary of the object on the screen using an electronic tablet and pen or analogous procedure.

These two basic approaches have their advantages and disadvantages. To use the advantages of CSG representation and B-rep in one solid model system, hybrid systems have been developed [Mantyla 1985]. With these systems users have the capability to construct the geometric model by either approach, whichever is more appropriate to the particular problem.

4.9 Manufacturing process selection

The selection of material and the manufacturing process is a multi-attribute decision made at the early stages of designing a component [Giachetti, 2001]. Designers are faced with many decisions among, which are the selection of the most appropriate material, and the most appropriate manufacturing process that is capable of forming the selected material to the desired shape economically. Often the designer has insufficient information and knowledge to effectively consider manufacturability aspects of the product design [Vliet et al, 2000] and therefore, most designers select a process based on their experience and intuition in addition to a guesstimation of many of the influencing factors [Ishii et al, 1999]. Generally, manufacturing process selection involves two steps [Esawi et al, 1998]. The first involves the screening of all available processes to determine whether they are technically capable of making the design. The second involves the ranking of those, which are successful, using economical criteria. The ranking step requires techniques of cost estimation. In seeking to achieve this, two

problems are encountered. The first is that the design is still in the conceptual stage and little information is available, the second is that conventional cost estimation techniques require detailed information and cannot easily be applied to widely diverse processes.

In the conceptual stage of design little information is available and few constraints have been specified so all possible manufacturing processes should be considered. As the design progresses to the embodiment stage, more information on the product becomes available and a set of constraints are specified. These are used to determine a subset of processes, which are capable of making the product [Giachetti, 2001, Charles, 2001]. Finally, as the design reaches its final stages and becomes detailed enough to allow cost evaluation, a single process can be selected. It is helpful at each stage to know the potential processes since this influences the next level of design decisions.

Bock [Bock, 1991] upgraded the computer aided material and process selector (CAMPS) that was created by Dargie in 1982 [Dargie, 1982]. Kunchithapatham [Kunchithapatham, 1996] created the design advisor around separate quality material and process searches and Giachetti [Giachetti, 1997] suggest another all-database solution for conceptual process selection. The Cambridge Engineering Selector (CES) is the only commercially available process selection software. It is discussed by Esawi and Ashby [Esawi and Ashby, 2000] and contains information of more than 100 different manufacturing process and process variations. To illustrate this research injection moulding has been selected as the manufacturing process.

4.10 Injection moulding

Injection moulding is the process that moulds plastic through heat and pressure,

by injecting molten polymer into the desired mould (figure 4.2). Injection moulding is the most commonly used process for producing plastics, [Rawabedeh, 1999] because as described in chapter 1, it gives a good surface finish and can be used for very complex shapes. The diversity of shapes that can be produced by this process is infinite. Injection moulding, although requiring a substantial capital investment, becomes very economically viable in mass production and gives a very low unit production cost. Injection moulding is generally used for the processing of thermoplastic materials because thermosetting plastics assume their final shape through heat and are moulded by direct stew transfer moulding, transfer moulding or compression moulding. Usually the products come out of the injection moulding machine in a ready-to-use condition and in most cases, the cost of production is significantly less than that of the products made by compression moulding [Sors, 1988].

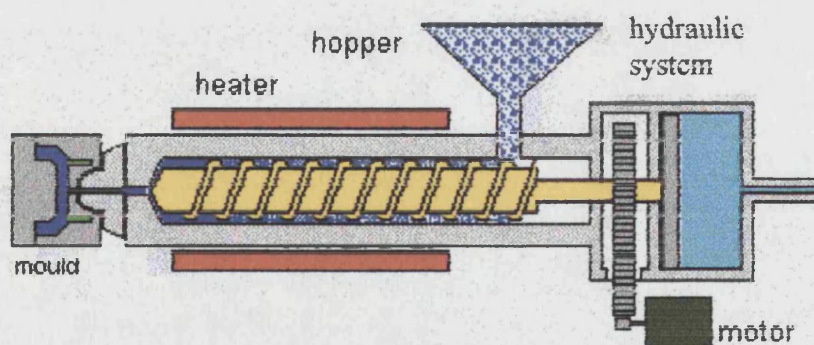


Figure 4.2: Injection moulding process [www.fp.keystage3dt.f9, 2001]

4.11 Design for injection moulding

Good design of injection moulded products produce a high quality product with few defects. The common defects such as sink marks on the surface, warpage, shrinkage and porosity can all be avoided if design consideration factors are taken into account [Joel, 1973]. Rules that have been developed for the design of injection mouldings [Monsanto, 1985, Chow, 1978] can help the designer to design products, which are easy to produce with good surface finish, a low number of defects and at an economic cost. Some of the rules of thumb used during design are related to component features for example, wall thickness, ribs, bosses, tapers, undercuts, holes, and threads [Bralla, 1986]. These rules are described in greater detail below.

Wall thickness must be as uniform as possible to eliminate part distortion, internal stress and cracking [Beck, 1970]. If different wall thickness is necessary in a part, the wall intersection must be blended gradually. Usually a fillet radius of 0.508 to 0.762 mm is suitable to eliminate sharp corners in order to reduce cracking due to notch sensitivity. Using ribs can increase rigidity and strength without increasing the wall thickness. The rib width is usually less than the attached wall thickness. The height of the boss should be twice its diameter while the thickness should less than 50% of the supporting wall thickness. A one-degree wall draft angle must be applied on the product to facilitate ejection. The distance between the edge holes is about three-times the diameter of the hole. External and internal threads should be less than 32 pitches and a clearance of at least 0.8 mm should be applied at the end of the threads.

4.12 The application of computers in cost estimating

Product cost is affected by many variables such as product complexity, material usage and the manufacturing processes all of which could change during the design stage. To estimate the product costs, numerous variables must be stored, retrieved and manipulated. In many cases consideration of all the cost factors may not be possible without utilising a computer. Ogunlana [Ogunlana 1989] outlines the following potential applications of the computer in cost estimation:

1. To speed up the process of producing cost estimates, cost plans and cost checking.
2. To store more data to aid estimating and cost planning.
3. To introduce statistical treatment into predictions of manufacturing costs.
4. Modelling manufacturing processes and/or cost simulation.

Besides the potential described by Ogunlana there are many advantages in using computers for cost estimating [William 1989] such as:

1. The effort required to do most estimates is reduced.
2. Manual searching of files for data is virtually eliminated because the knowledge base contains much of the information.
3. The calculation, summation and preparation of output reports is automated, therefore the estimators effort and cost is eliminated.
4. The number of mistakes associated with manual effort should be minimised.

5. Information that is much more comprehensive can be stored in a knowledge base and checking and correction is reduced therefore the accuracy is improved. There is a practical limit to accessibility of information stored in files for traditional cost estimating; a characteristic that does not appear to exist in a properly designed computer based system.
6. Adding new or revising existing information is easier than in typical manual systems and this may be of major importance. In many cases, files that are manually accessed may require restructuring. In others, the new information needs to be cross-referenced making accessibility difficult.
7. Similar estimates can be grouped for detailed analysis and ways to improve estimate success rate may be identified through this analysis. For example, adjustments to the knowledge base may be necessary. Also, specific improvements required in manufacturing operations to improve competitiveness might become obvious.

4.13 Computer Aided Conceptual Cost Estimating

Using computers to estimating the cost in the conceptual stage of design, allows preliminary cost estimates to be made using only minimal information. It helps guide the product development process from concept through to the detailed design stage. Computers have the capability to store, retrieve and manipulate the data necessary to carry out the engineering required throughout the design stage. The high speed of data processing in computers can enable two or more software programs to be run simultaneously and this can be utilised to perform the process of conceptual cost

estimation. Also computer networks enable involved users such as designers and manufacturers, to access the related cost and product information at the same time.

4.14 Software selection

The design stage takes much time, effort and experience and is a significant part of the cost. Using appropriate computer aided design software could facilitate the design process and reduce the cost of the design stage. There are many different software packages that can be used for developing a new product. Most of them are powerful enough, but as they have been typically designed for slightly different purposes, the process of software selection, could be very important to reduce the time and effort necessary for design.

Komoski [Komoski, 1995] outlines the following seven-step process for responsible software selection.

1. Analyse Needs
2. Specify Requirements
3. Identify Promising Software
4. Read Relevant Reviews
5. Preview Software
6. Make Recommendations
7. Get post-user feedback

As Komoski outlines, a “need” is the difference between *“where we are now”* and *“where we would like to be”*. This analysis determines which software will be used to meet the goals. Factors to consider in specifying requirements include compatibility with available hardware, costs, user friendliness and access to technical support. Catalogues and the Internet are ways to identify promising software. After a list of promising software has been identified it is possible to narrow or expand the list by reading relevant software reviews. Then a preview is necessary to find whether the software is able or not to meet the criteria.

After potential software has been previewed, it is possible to make recommendations for purchase. Evaluating the relative importance of each selection criterion, and creating a written record outlining the reasons why a piece of software is recommended are very important.

The first six steps of Komoski’s method can be used for a wide range of software selection but the last step can only be used by the companies that periodically are faced with new software selection and the feed back is a significant factor in their activities.

4.15 Ideas software

Ideas software has been chosen for this research work. It is a powerful software that enables designers to create either wire-frame or solid models. The building, testing, and analysis of the product models are possible in Ideas. Modelling parts, assembly and also testing for failure, bending, interference between components, or other analysis is possible to see if the part sizes and load carrying capabilities are adequate. The preparation of the computer presentation include areas such as rendering, videos and

realistic photographic scenes. The preparation of actual working drawings of all components can be produced enabling the supplier to manufacture the prototype. From the drawings, quotes on each part can be requested from the supplier, and a cost for the prototype can be more accurately determined. The main screen view of the Ideas design software is shown in figure 4.3. a detailed description of the functionalities is provided in appendix A.

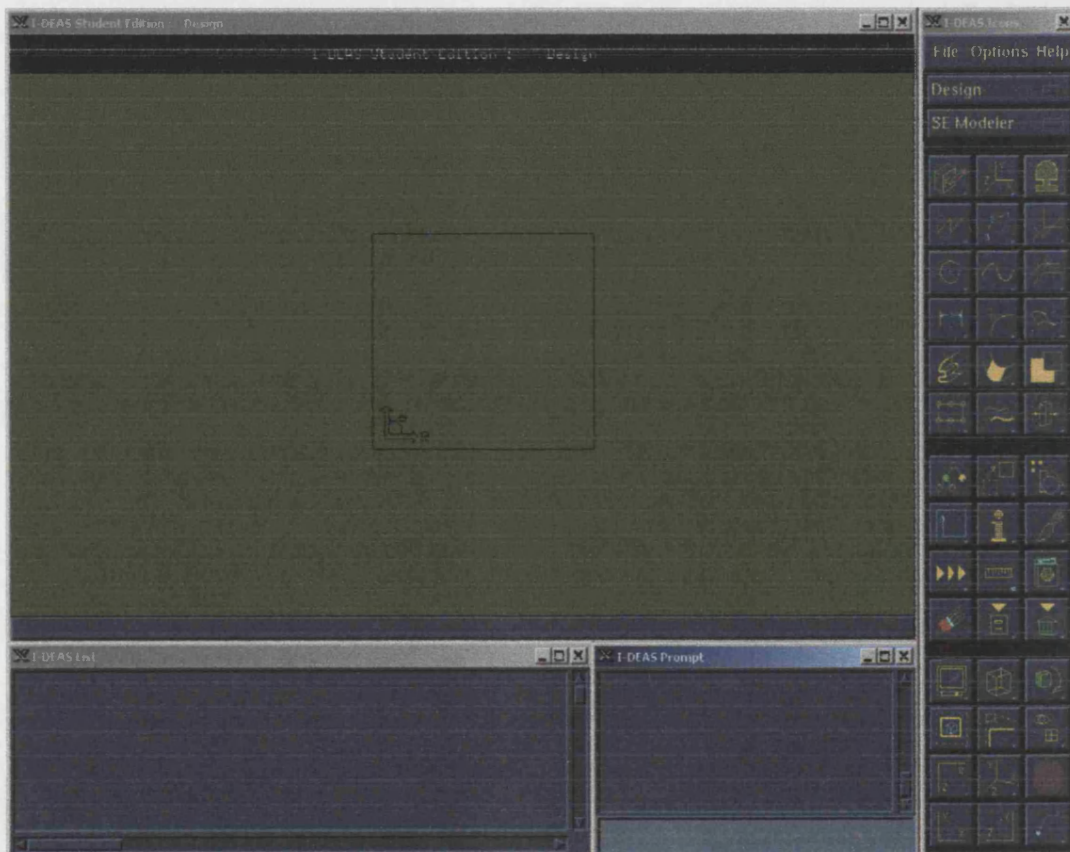


Figure 4.3: The main screen view of the Ideas design software

4.16 Visual FoxPro Package

Microsoft Visual FoxPro is an extremely powerful tool for quickly building database applications [Hancock, 2001]. Its easy programming language offers developers a set of tools for building and manipulating databases for desktops and servers. Visual FoxPro provides the tools require to create and build modern, scalable, multi-tier applications that integrate client/server computing and the Internet.

Visual FoxPro enables programmers to create and manage tables of data individually and relationally from many sources. In addition, programmes can access or manipulate all kinds of data quickly, whether they are on a local disk, a network, or the Internet. The main screen view of the FoxPro software is shown in figure 4.4 with a greater level of detail being provided in appendix B.

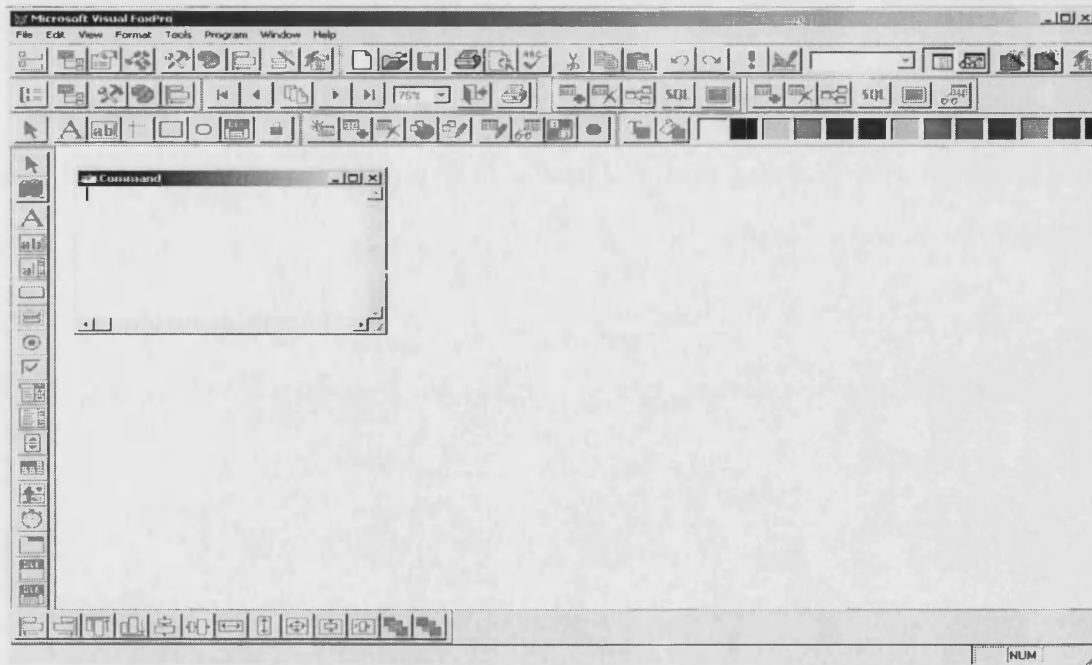


Figure 4.4: The main screen view of Visual FoxPro software

Chapter 5

Building up injection moulding products using sections

5.1 Introduction

Manufacturing is the process of converting raw material into useful products. Today there are many different manufacturing processes available, to produce products such as; plastic injection moulding, sand casting, milling, die casting, shell moulding, material removal via chemical or electrical methods, machining, sheet metal forming, forging, rolling, extrusion, bending composition, spray deposition, etc.

Obviously, there are significant differences among manufactured products. Some of them are ready to use after the first process, others require a series of secondary operations to be performed, to make them ready for use. In addition, joining and assembling parts is one of the major tasks for many companies, as most of today's complex products, are produced using a set of parts that are joined or assembled together.

For an assembled product, the cost of manufacture could be estimated, using the summation of the manufacturing cost of the individual components, and the cost of the assembly process. But, for complex injection-moulded products, that can be produced, through a single operation, a cost estimate may not be achieved using the same procedure as for assembled products. However an injection moulded component can also be considered as consisting of many subparts and features. How this is achieved has been the subject of much research.

Many researchers have adopted the volume decomposition approach, which decomposes an object into a series of volumes, and then attempts to recognise features from the volumes [Case 1999, Chin 1996, Lee 1998]. The majority of researchers have used this approach to extract machining features, for subsequent assembly or process planning operations. In many cases a feature-based design model, based on an integrated geometric modelling system that, supports both feature-based modelling and feature recognition has been used. This type of feature decomposition however is not applicable for an injection-moulded product, as it undergoes a different method of manufacturing.

To estimate the cost of injection-moulded products, a new feature based construction approach, is proposed by the author of this research. In this approach an injection-moulded product is constructed from a library of three-dimensional features.

The proposed library of features, and how features are used to develop injection moulded products, are described later in this chapter.

5.2 Feature-based design

Feature-based design means, that parts are designed by starting with a simple feature such as extrusion or revolution i.e. a cylinder or a block, and then modifying this by attaching other features such as holes, slots, etc. to its various faces [Lng 2000, Trika 1997]. The designer specifies the position, size and orientation of these additional features. In injection moulding the two main factors which affect the material cost and tooling cost are the part size and the complexity of its shape. These in turn dominate the product cost [Chen and Liu 1999]. In fact in most manufacturing processes, manufacturing cost are directly related to the part complexity, which is determined by its geometric features. According to the concept of feature-based

design, a part is constructed, edited, and manipulated in terms of its features with certain spatial and functional relationships. Therefore, the size and the shape complexity of a part are largely dependent on the size and shape complexities of the features in the part and their spatial relationships. In other words, the size and complexity of a part varies with the addition, placement and editing of features during the design process.

5.3 Feature definition

Features are derived from the reasoning processes used in various design analyses and manufacturing activities and are usually strongly associated with a particular application domain [Bradley, 2001; Dixon 1988]. Hence according to the domain they originate from there are a number of definitions of features. Pratt and Wilson [Pratt and Wilson 1985] define features in the engineering domain, as “*A feature is a region of interest on the surface of a part*”. Peihua [1994] defines a feature, as “*A feature is a geometric surface that can be represented by either planar, quadratic, or parametric equations*”. It is defined by specific syntax and contains various data such as mathematical representation; classification which can be either protrusion or depression; orientation with respect to other features or a user defined coordinate system; and its geometric and topological structure. A generalised definition of a feature is described by Henderson [Henderson 1995] that is: “*features are defined as geometric and topological patterns of interest in a part model which represent high level entities useful in part analysis*”.

In many cases, the geometry of a feature needs to be considered, the feature is then termed a geometric feature [Lenau and Mu 1991]. Geometric features provide an alternative component representation that is suitable for a wide range of activities,

thus filling the gap between design and manufacturing [Case and Wan, 1999]. Because of this potential, geometric features have been used in many CAD or CAM applications, such as design [Case and Gao, 1993], injection moulding [Ashaab, 1995] manufacturing cost analysis [Nieminen and Tuomi, 1991], and process planning [Gindy et al., 1993]. Geometric features can be grouped together to form a geometric model. Feature recognition as well as geometric feature being used to construct a geometric model.

5.4 Feature recognition

The process of identifying features within a geometric model of a part can be defined as feature recognition [Mantyla, 1996]. A feature is defined by a set of geometric entities that have topological and geometric patterns unique to the feature. Various pattern matching methods such as syntactic pattern recognition, neural networks, and most often graph matching have been used to recognise features in geometric models [Sakurai 1996]. However, when features intersect, they lose their unique patterns. Thus, recognition of intersecting features has remained elusive to feature recognition methods that rely solely on pattern matching. Also when features intersect, the region of intersect can be interpreted as consisting of non-intersecting features in several different ways.

Researchers have developed several different feature definition and feature recognition methods. Xu and Hinduja [1998] outline the five following stages for features recognition:

1. Feature detection.
2. Volume construction.
3. Feature verification.

4. Work piece updating.
5. Feature method classification.

In the first stage, the system identifies the faces, which give rise to a feature. In the second stage, the corresponding feature volume is constructed, this is followed by feature verification, which checks the validity of the feature and modifies it if necessary. Next, the feature volume is glued on to the work piece to get the intermediate shape, which is referred to as work piece updating. In the final stage, each feature is examined and classified.

Henderson [1990] proposed a feature recognition method that searches for feature hints, which are topological and geometric patterns that suggests the possibilities of the existence of features. It then generates volumes from the hints and verifies the existence of the features with the volumes. The volume generation step achieves the effect of face extension, i.e. restoring the topological and geometric pattern unique to a feature. The recogniser generates some different interpretations of intersecting features. Each hint is a subset of the topological and geometric patterns of a feature.

In previous feature decomposition studies, a complex shape was often decomposed into simpler shapes to facilitate representing the shape and performing various operations on the shape. Therefore it can be true that a complex part is a set of simple volumes that are identified through the use of various rules. This view is especially sensible in the assembly process. An injection moulding can be considered as an assembly of primitive shapes. An important foundation for developing cost estimation algorithms for injection-moulded products is the development of a feature taxonomy that relates to this “growing” of a component by the assembly of features. By representing the assembly by means of features, the link between design and other functions can be improved and, since many other functions deal with abstracted

information, the representation of a component by an assembly of features can make the designer's task somewhat easier.

5.5 Generic features for injection moulded products

To develop a set of generic features for injection-moulded products, fifty injection moulded products were analysed. Some of them are shown in figure 5.1.

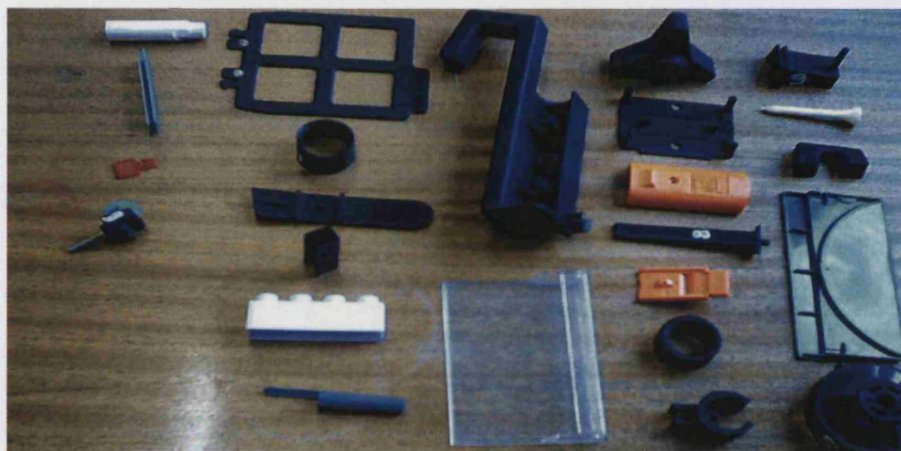


Figure 5.1: A selection of injection moulded products

From the analysis, it was found that, the products could be constructed from 11 basic features. It was also found that, there are six common composite features that are useful when designing injection mouldings, and these were added to the features set. From the point of using computers in the design process, it was apparent that, using such a feature set could reduce the effort necessary for developing an injection moulded product. The fifty injection moulded products examined were boxed shape engineering products. The proposed basic shapes would be capable of constructing 90% of engineering products. For all injection moulded products 80% could be constructed using the basic shapes. To illustrate this one of the basic shape proposed

would allow for some of this development. The basic shapes and the composite shapes are described below.

1. Rectangular plate.
2. Cylinder.
3. Hollow cylinder.
4. Wedge.
5. Sphere.
6. Cone.
7. Pyramid.
8. Torus.
9. Half hollow sphere.
10. Half hollow cylinder.
11. Curved plate.
12. Combination of a rectangular plate and a negative half cylinder.
13. Combination of rectangular plate and a positive cylinder.
14. Combination of two rectangular plates.
15. Combination of three rectangular plates.
16. Combination of four rectangular plates.
17. Combination of a curved surface and a wedge.

5.5.1 Rectangular plate

From the analysed parts, it was found that a rectangular plate was present in approximately 80% of the injection moulded products, and therefore, could be assumed to be a basic injection moulded feature. To develop a rectangular plate, a 2D rectangle was drawn; its three edges, and one edge angle, were specified (figure 5.2). Then, it was extruded as a solid. Through changing the solid shape parameters,

a wide range of different plate features are possible. Some of the possible plate shapes are shown in figure 5.3.

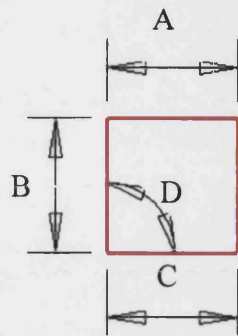
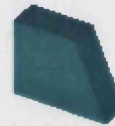


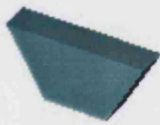
Figure 5.2: A dimensioned two-dimensional rectangle for developing into a plate



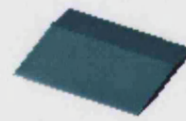
i- Basic plate feature



ii- Changing parameters C



iii- Changing parameters A and D



iv- Changing parameters A, C and D

Figure 5.3: A basic plate feature with three alternative shapes

5.5.2 Cylinder

Cylindrical features are also very popular in injection moulded products. 60% of the analysed products included at least one cylindrical feature. Hence a cylinder can be assumed to be a basic shape for injection moulded products. To develop such a shape, a simple 2D circle was drawn (figure 5.4). The circle was then extruded to produce a solid shape. The creation of many different flat cylindrical, and bar shapes

produce a solid shape. The creation of many different flat cylindrical, and bar shapes is possible by changing both the diameter of the circle, and the extruded distance. In addition, a cone can also be created by applying a draft angle. Four possible feature designs are shown in figure 5.5.

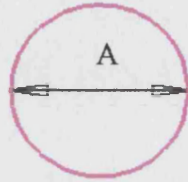
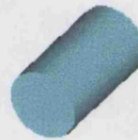


Figure 5.4: A two dimensional circle for developing into a cylinder



i- Basic cylindrical feature



ii- Changing extrude distance



iii- Changing extrude distance and applying draft angle



iv- Changing parameters A and B

Figure 5.5: Proposed basic cylindrical feature with three alternative shapes

5.5.3 Hollow cylinder

Fifty percent of the analysed products had at least one hollow cylindrical section, and it was therefore, assumed to be a basic shape for injection moulded products. Two non-concentric circles were drawn (figure 5.6). This 2D shape was extruded to provide a basic hollow cylindrical feature. Using this feature enables the

a non-uniform wall thickness would be possible by changing the distance between the centres of the circles. In addition, it is possible to create hollow cones, by adding a draft angle, and extruding simultaneously. Figure 5.7 shows four possible hollow cylindrical shapes.

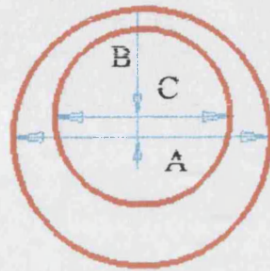


Figure 5.6: Two non-concentric circles for developing into a hollow cylindrical basic shape



i- Basic hollow cylinder feature



ii- Changing parameters A,B,C and extrude distance



iii- changing parameters A and B



iv- Changing Parameter B and applying draft angle

Figure 5.7: Proposed basic hollow cylinder feature with three alternative shapes

5.5.4 Wedge

From the analysis, a wedge shape was present in approximately 35% of the injection moulded products. The author identified this as another basic shape. To develop a basic wedge shape, a 2D triangle was drawn. Two edges, and the angle between them, have been specified (figure 5.8). The triangle was then extruded to create a 3D wedge shape. Creating a wide variety of wedge shapes is possible by changing the wedge dimensions, angle or extruded distance. In addition, creating pyramid shapes are possible if a draft angle is applied. The basic wedge shape, and three alternative shapes is depicted in figure 5.9.

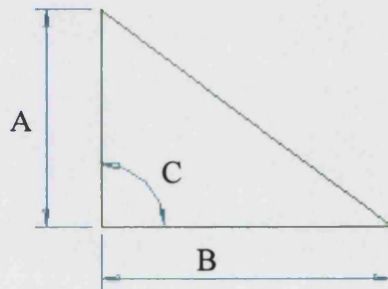


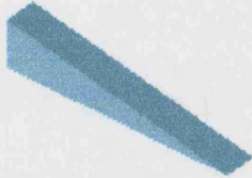
Figure 5.8: A simple 2D triangle for developing into wedge shaped feature



i- Basic wedge feature



ii- applying draft angle



iii- changing parameters A and B



iv- Changing parameter B

Figure 5.9: Proposed basic wedge feature with three alternative shapes

5.5.5 Sphere

Only a small number of solid sphere shapes were found in the 50 injection moulded products analysed. It is, however, the author's view, that there is a need for a basic solid sphere shape to enable a larger set of injection moulded products to be covered. To develop a sphere feature, a 2D crescent (figure 5.10) was selected, and revolved around its axis. Figure 5.11 shows a simple sphere feature and three alternative shaped sphere features.

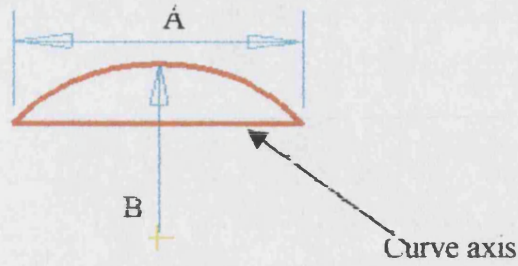
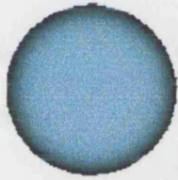
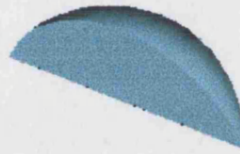


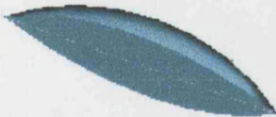
Figure 5.10: A simple 2D crescent for developing sphere features



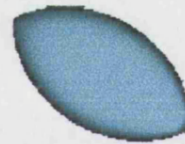
i- Basic sphere feature



ii- Changing revolve angle



iii- Changing parameter A and revolve angle



iv Changing parameter B and revolve angle

Figure 5.11: Proposed basic sphere feature with three alternative shapes

5.5.6 Cone

Again only a small number of solid cones were identified in the injection moulded products. It is also acknowledged that a solid cone can be created by

applying a draft angle to a solid cylinder (see figure 5.5). It is again, however, the author's view that a basic cone shape is helpful in developing injection moulded products. This is because; a solid cone is much easier to develop using the basic shape instead of developing it via the solid cylinder feature. Also, a basic solid cone is much more visible for the designer to choose from the menu during the design process. To develop a cone shape, a 2D trapezoid was chosen. However one of its edges was replaced with a curve, (figure 5.12) to provide a capability of developing cones with curved surfaces. The shape was then revolved around its axis. Figure 5.13 shows the proposed basic cone shape and three alternatives. (Note that by moving the basic shape off axis a hollow cone can be produced.)

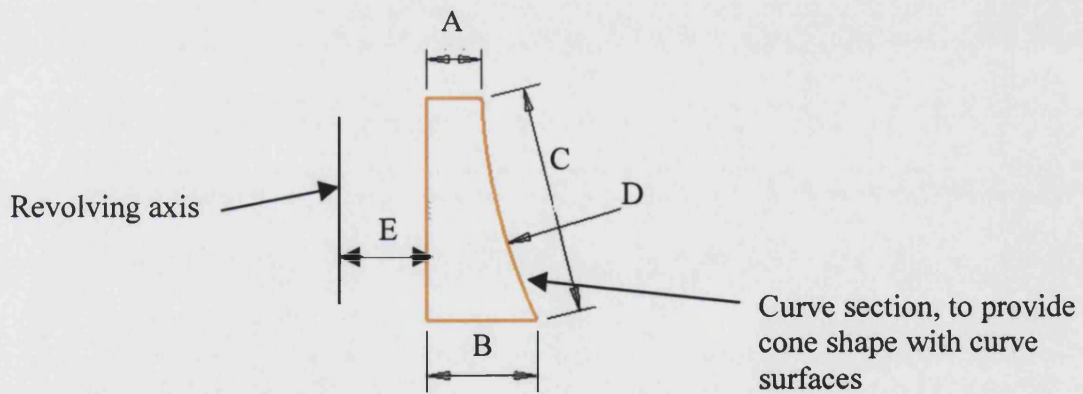
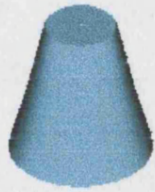


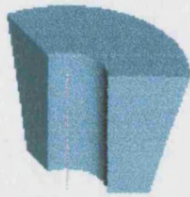
Figure 5.12: Proposed shape for making a basic cone



i- Basic cone feature ($E=0$)



ii- Changing parameters A and D



iii- Changing parameter E and revolving angle



iv- Changing parameter C and revolving angle

Figure 5.13 Proposed basic cone feature with three alternative shapes

5.5.7 Pyramid

As with the cone and the sphere, pyramid shapes were found in a small percentage of the products analysed, but it is again the author's view that a basic pyramid feature is important, and could make the design task somewhat easier. To enlarge the domain of features, that can be created using the basic pyramid shape, a 2D triangle has been drawn, and all three edges were made curves (figure 5.14). These curved edges could help designers to design a wide variety of pyramid features with or without curved surfaces. The basic 2D shape was then extruded, and a draft

angle applied to create the solid pyramid. The basic pyramid shape and three alternative shapes are shown in figure 5.15.

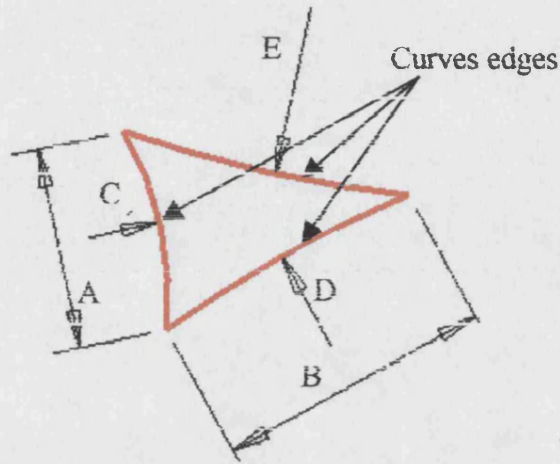
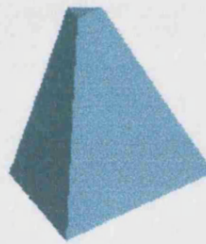


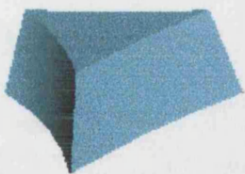
Figure 5.14: The proposed base shape for creating pyramid features



i- Basic pyramid feature



ii- Changing parameters C,D, and E



iii- changing extrude distance



iv- Changing parameters A, B and extrude distance

Figure 5.15: The proposed basic pyramid feature with three alternative shapes

5.5.8 Torus

The torus is another basic shape used in the design of injection moulded products. However, the numbers of torus feature found in the examined products were few. To develop a torus, a circle was drawn and a chord replaced one section of its circumference, and the rest of the circumference was replaced by two curves (figure 5.16). The line section allows the designer, to design a flat-bottomed torus and the radii of the curved sections could provide different surface forms for the torus. To develop the basic torus the 2D shape is revolved around an axis. A wide variety of torii can be created using different curve radii, straight line and centre of rotations (figure 5.17). Creating torii with an internal or external flat surface is possible.

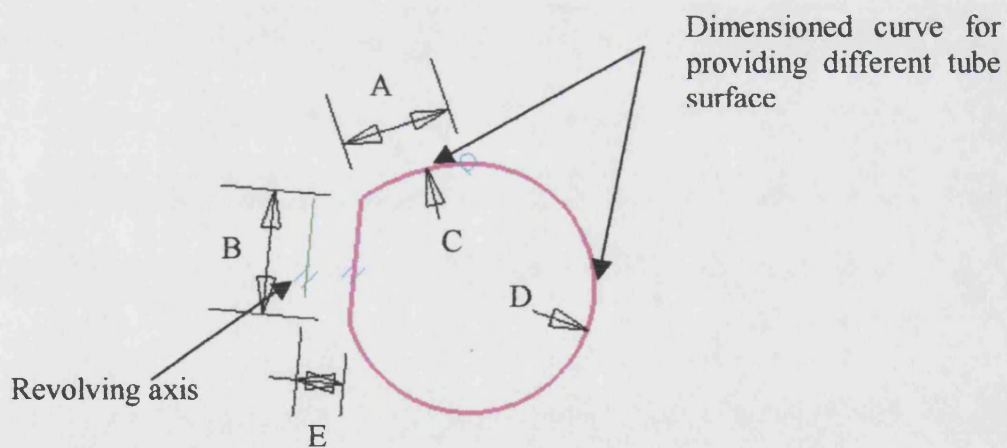
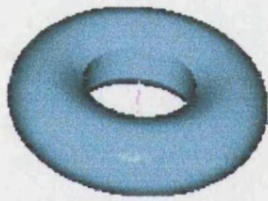
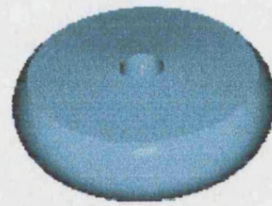


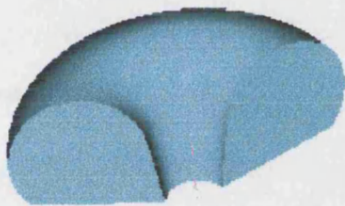
Figure 5.16: The proposed base shape for creating torus features



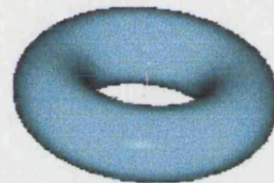
i- Basic torus feature



ii- Changing parameters C, and D



iii- changing parameters C, D,
and revolving angle



iv- Changing parameters B, and A

Figure 5.17: Proposed basic torus feature with three possible alternative shapes

5.5.9 Half hollow sphere

There was not a half-hollow sphere found in the injection moulded products investigated. However it is again the author's view that there is a need for a basic half-hollow sphere feature to provide greater coverage of the product domain. To develop this shape, a 2D half tube as shown in figure 5.18, was drawn and was then revolved around an axis to create the half hollow sphere feature. Some of the capabilities of this basic shape are shown in figure 5.19.

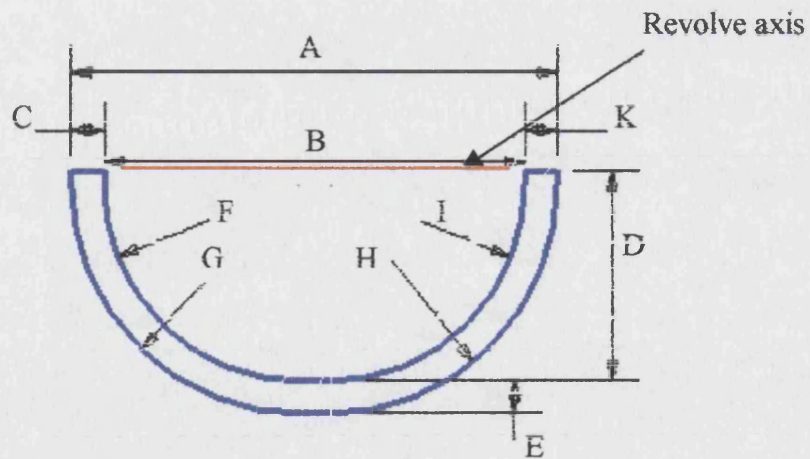
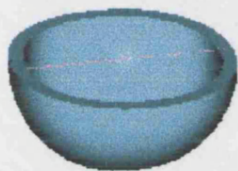
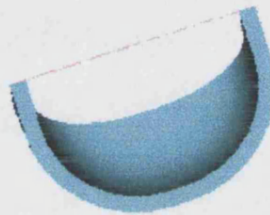


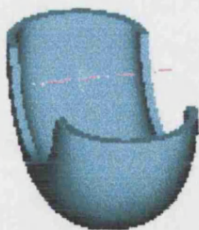
Figure 5.18: The Proposed basic shape for creating half hollow sphere feature



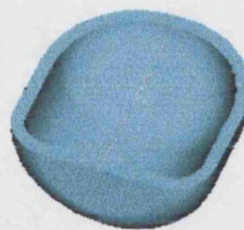
i- Basic half hollow feature



ii- Changing revolve angle



iii- changing revolve axis



iv- Changing parameters F and G

Figure 5.19: Proposed basic half hollow sphere with three alternative shapes

5.5.10 Half hollow cylinder

Cylindrical sections are popular in injection moulded products. As it has been mentioned in section 5.5.2, 38% of the injection moulded products analysed contained at least one half cylindrical shape. To develop a basic half hollow cylindrical shape, two 2D concentric half circles have been drawn, their ends connected, (figure 5.20) and then extruded to provide the basic shape. Various parameters can be altered to create a wide variety of shapes (figure 5.20).

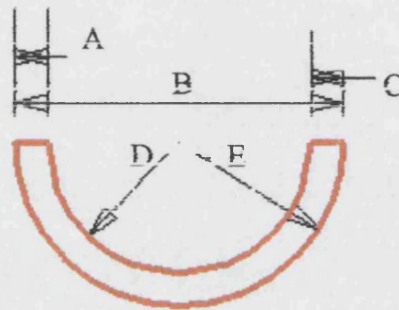


Figure 5.20: The proposed basic shape for creating half hollow cylindrical feature

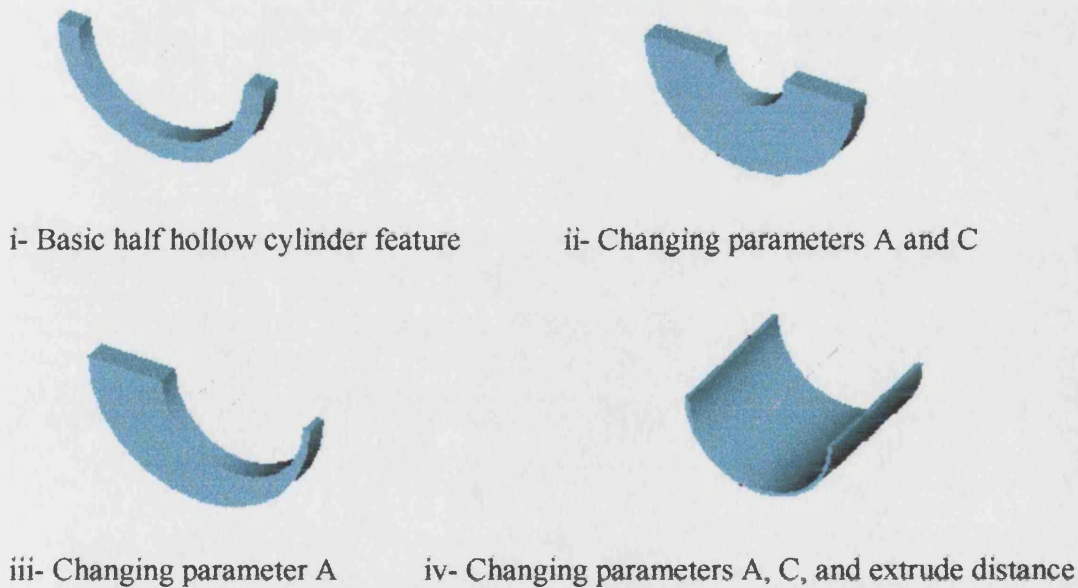


Figure 5.21: The proposed basic half hollow cylinder feature with three alternative shapes

5.5.11 Curved plate

A curve plate was present in about 50% of products analysed, and therefore, could assumed to be a basic shape. To develop this basic shape, two 2D concentric curves were drawn, and their ends connected (figure 5.22). This shape was then extruded to provide a plate curved. This feature enables the designer to design a wide variety of curved plates. For example; creating flat surfaces and half circular surfaces are possible via changing the shape parameters. Figure 5.23 illustrates the proposed basic curved plate and three alternatives.

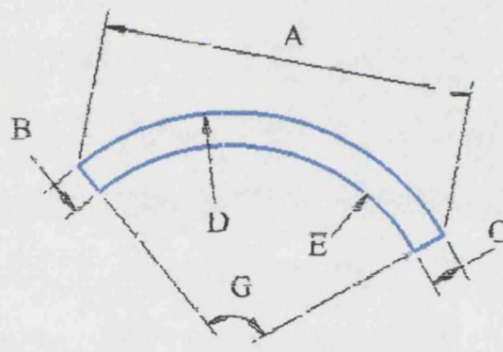


Figure 5.22: The proposed basic shape for developing the half hollow cylindrical features

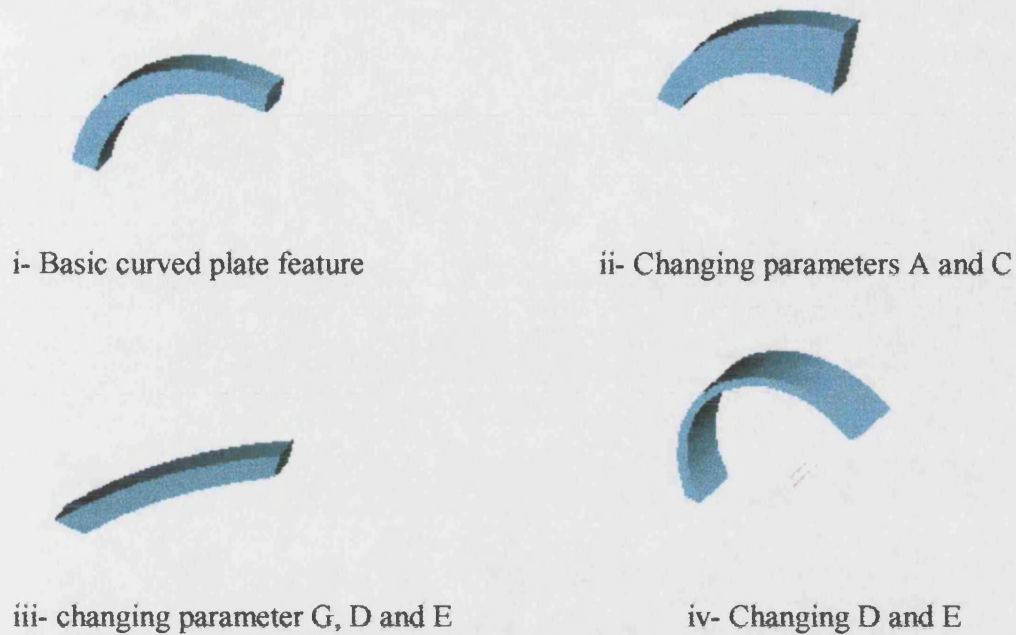


Figure 5.23: The proposed basic curved plate with three alternative shapes

5.5.12 Combination of a rectangular plate and a negative half cylinder

As described in section 5.5, some common combinations of two or three basic shapes have been identified in the injection moulded products analysed. Although, it is possible to design these combinations, using the basic shapes, their use could reduce the time and effort necessary for developing an injection moulded product design. The combination of a rectangular plate cube and a negative half cylinder was found in 24% of the injection moulded products. To develop a combined basic shape, a 2D rectangular plate was drawn and a part of its top edge replaced by a negative half cylinder (figure 5.24). This was then extruded to give the basic 3D features. Creating a wide variety of combined shapes is possible by

changing the shape parameters. The basic feature and five alternative shapes are shown in figure 5.25.

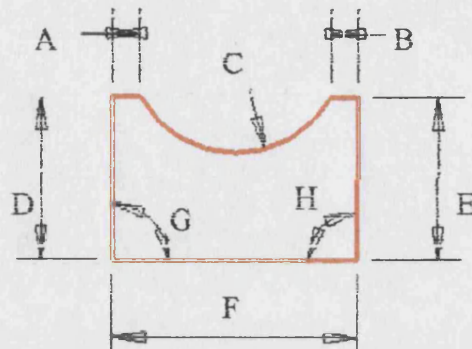


Figure 5.24: The 2D proposed basic shape for developing into basic combined feature

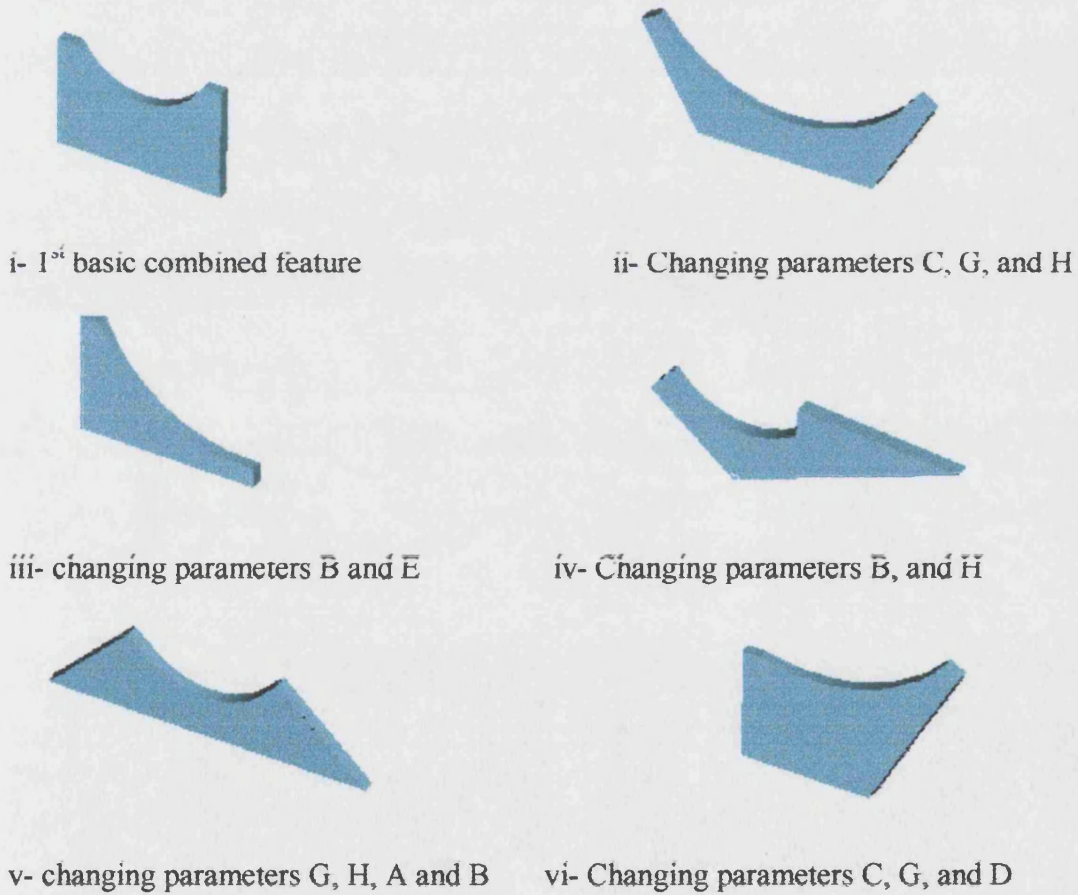


Figure 5.25: The 1st basic combined feature with 5 alternative shapes

5.5.13 Combination of a rectangular plate and a positive half cylinder

A combination of a rectangular plate and a positive half solid cylinder is also proposed as a basic shape for injection moulding product design. This is because, 22% of the examined products also contained this combination. It is the reverse of combination 5.5.12 (figure 5.26). Figure 5.27 presents the basic shape and some alternatives.

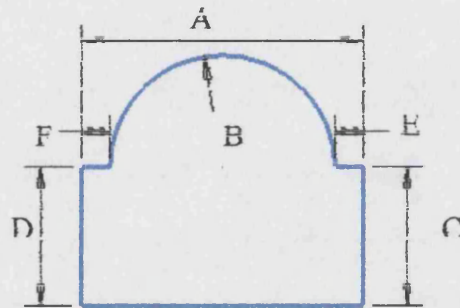


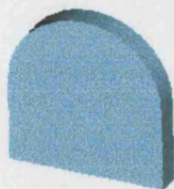
Figure 5.26: A proposed base shape for developing a synthesis basic shape



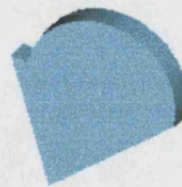
i- 2nd basic feature



ii- Changing parameters A, F, E, and C



iii- changing parameters E and F



iv- Changing parameters E, C

Figure 5.27: The 2nd proposed combined basic feature with 3 alternative shapes

5.5.14 Combination of two rectangular plates

A combination of two flat plates helps the designer to design a wide range of corner features by changing the including angle. The proposed 2D basic shape is shown in figure 5.28. This basic shape was then extruded to provide the 3D combined basic feature. Figure 5.29 shows the combined basic shape and three other possible alternatives.

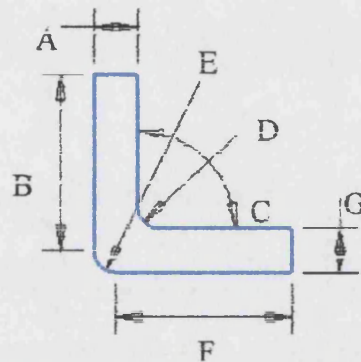


Figure 5.28: The 2D proposed basic shape for developing into the 3D basic combined feature

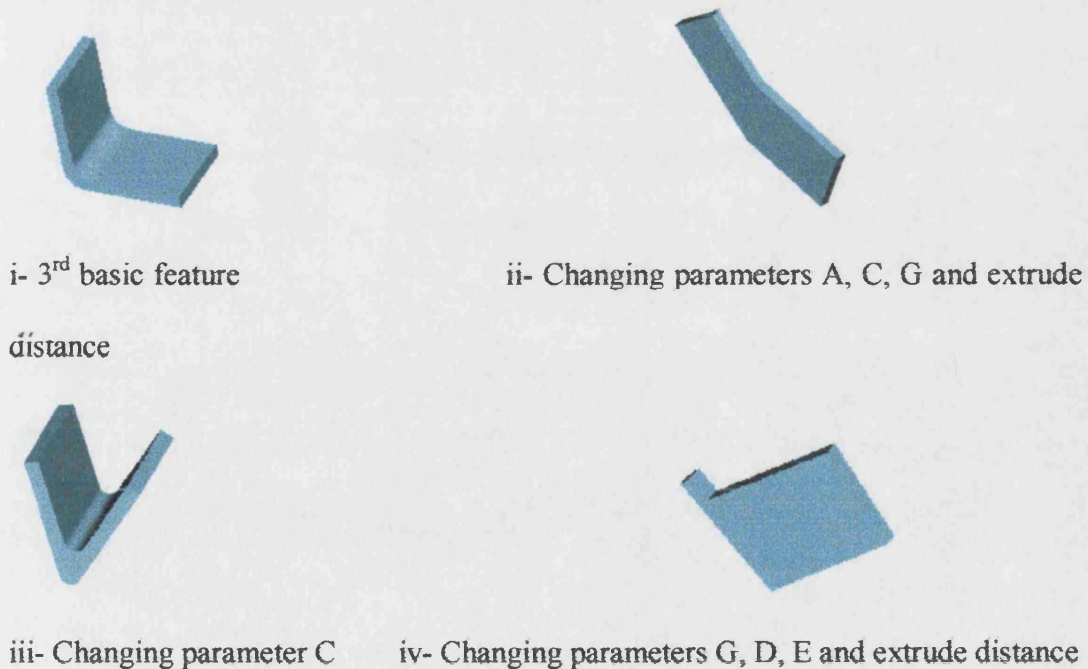


Figure 5.29: The 3rd proposed combined basic feature with three alternative shapes

5.5.15 Combination of three rectangular plates

Thirty percent of the products analysed contained at least one feature that was a combination of three flat plates. As described before, it is possible to use three flat plates feature to create this shape, but it was considered to be beneficial to design process to identify it separate feature. The 2D basic shape proposed is shown in figure 5.30. The two corner angles are restricted to between 1° and 180° , but the wall dimensions and extruded distance are unlimited. The 4th combine basic feature and 7 alternative shapes are shown in figure 5.31

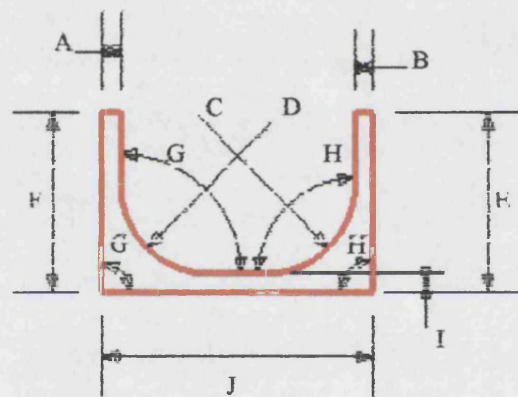


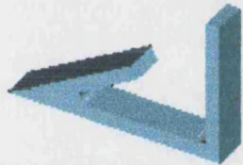
Figure 5.30: The proposed 2D basic combined shape for developing into the 4th basic combined feature



i- 4th basic feature



ii- Changing parameters A, B, C and D



iii- Changing parameters C, D, G, H



iv- Changing parameters A, F, and G



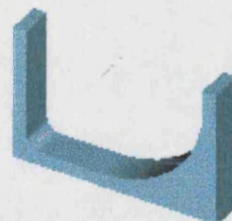
v- Changing parameters I, F, and E



vi- Changing parameters C, D, G, and H



vii- Changing parameters C, D, G and H



viii- Changing parameters D

Figure 5.31: The proposed 4th basic combined feature with 7 alternative shapes

5.5.16 Combination of four rectangular plates

The combination of four flat plates is assumed to be another of the proposed basic feature for injection moulding products. This basic shape, with radiused internal and external corners is shown in figure 5.32. The basic shape was then extruded to provide the 3D basic feature. The basic shape and three alternative shapes are shown in figure 5.33.

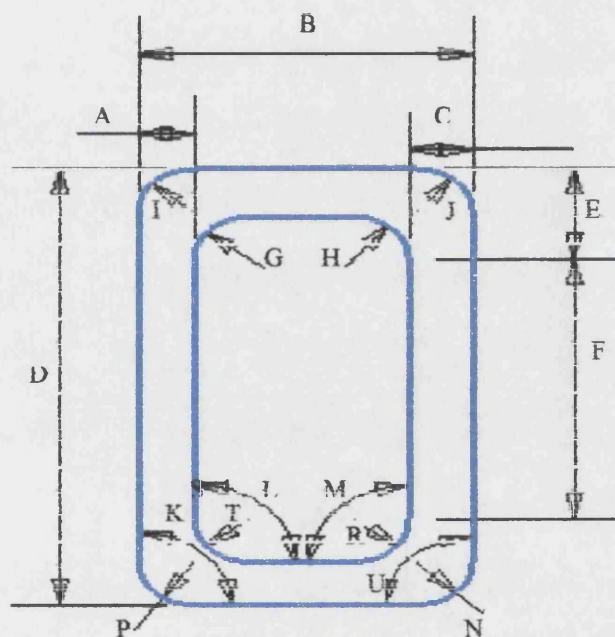


Figure 5.32: The proposed 2D basic shape for developing into 5th combined feature



i- 5th basic feature



ii- Changing the radius of the corners (F, G, D, E, N, H, P, I)



iii- Changing parameters K, M



vi- Changing parameter P

Figure 5.33: The proposed 5th combined basic feature with 3 alternative shapes

5.5.17 Combination of a wedge and a positive half cylinder

In the injection moulded products analysed, some sections were identified that consisted of a wedge and a positive half cylinder. Again it was considered that this should be included as a feature to save design time. To develop the basic shape, a triangle was drawn, and one of its edges, replaced by a part of a circle (figure 5.34). This shape was then extruded to provide the 3D basic shape. The angle between the two edges of the triangle can be changed from 1° to 359° degree. Figure 5.35 shows the basic feature and three alternative shapes.

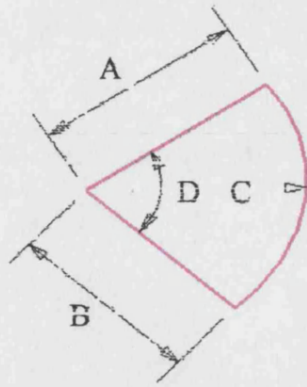


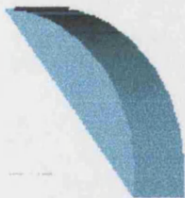
Figure 5.34: The proposed 2D basic shape for developing into the 5th combined feature



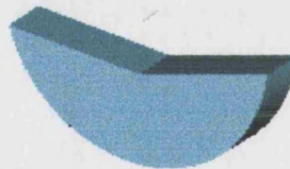
i- 6th basic feature



ii- Changing parameter A, B, and C



iii- Changing parameter B



vi- Changing parameters D

Figure 5.35: The proposed 6th combined basic feature with three alternative shapes

5.6 Building up a Products using the developed features

The process of part design is a complex task involving many factors and requires a lot of time and effort. However many packages are available and many techniques are available to facilitate the design process, but it is still not an easy task. The main advantage of using pre-defined features is, that they have already been designed and have the ability to be rapidly changed to create a large number of different products. Some of today's design packages, already included a set of pre-defined basic features, that could be helpful during the design process, but they are not comprehensive enough for product design. It is the author's view that the proposed basic features that have been described in section 5.5, could overcome this shortcoming for injection moulded products. The process of building up an injection moulded product through the use of the proposed basic features could be performed in the following five steps:

Step1 Choose the start feature

The basic feature could be any section of the new product but the biggest section is preferred (see section 3.7). The nearest proposed basic feature could be used for the section.

Step 2 Edit feature dimensions

The original dimensions of the feature need to be changed for creating the necessary sections of the product features. For the first feature the process should be continued in step 5.

Step 3 Adding and joining other features

To create the injection moulding product, the basic features need to be joined to other feature.

Step 4 Editing developed part

In the injection moulding product design, there may be some necessary changes in the developed product such as corners fillets, adding especial sections, which are not possible to create, using the proposed features. These necessary changes are assumed to be performed during this step.

Step 5 Select the next feature

The next feature should be chosen from the features, which relate to the chosen features. The process steps are then repeated from step 2 covering all product the features.

The main benefit of building up injection-moulding products, using the proposed basic features is that, they can also be used for the process of cost estimation for injection moulding products. This process is described in the next chapter. The proposed “building up” product methodology is illustrated in the following steps by the example of an injection moulded product as shown in figure 5.36. The product consists of 21 distinguishable sub-parts, which are labelling with B1 to B21. the next section illustrate how a designer could use the feature build up to create such a product.

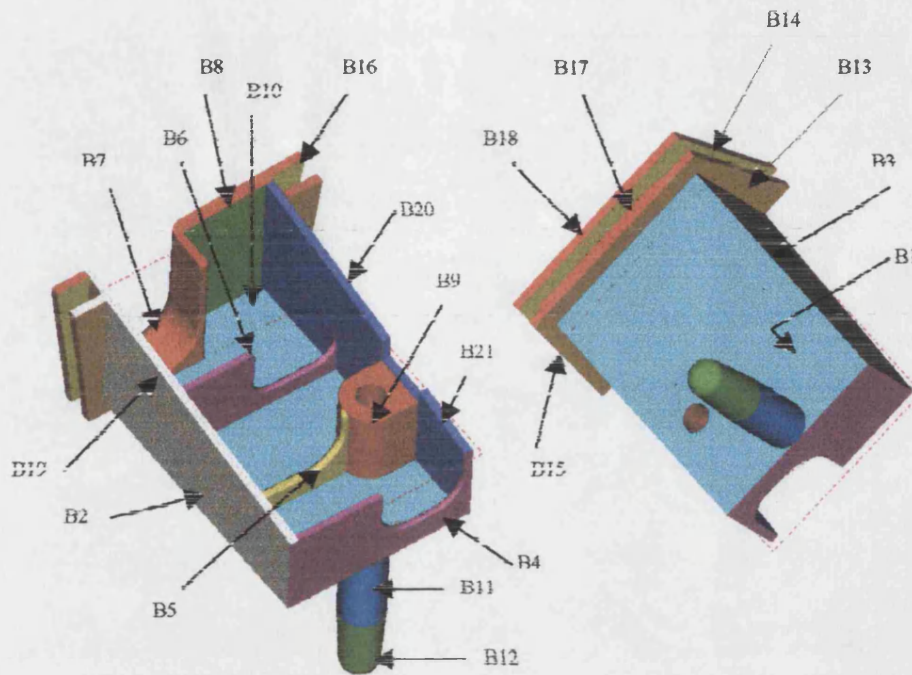


Figure 5.36: Two views of an injection moulded product

Step 1 Selecting the initial feature

As it is apparent from figure 5.36, the sub-parts B1, B2 and B3 together, could be the biggest sub-part of the product. This sub-part is shown in figure 5.37 and is assumed to be the first feature of the product. The nearest basic feature to this sub-part is the combination of three rectangular plates (see section 5.5.15). Editing the dimensions of this feature, is, the only necessary effort, for creating the sub-part.

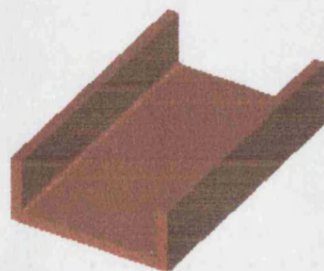


Figure 5.37: The proposed largest sub-part of the product

Step 2: Editing the dimension of the basic feature

In Ideas, there are two possibilities that can be used for editing the dimensions of the basic feature namely, individually and cumulative. To change the dimensions individually, it is necessary to click on a dimension, and then, changing the specified value or formula, in the table provided. To change some or all dimensions together, it is necessary to click on the feature, and then click on the changing icon, and next click on the dimension value icon. All the dimensions of the feature are then available to change. In both conditions, the feature needs to be updated after any changes in the dimensions.

As described in step 1, the combination of three rectangular plates is the nearest feature for developing the sub-part. Therefore, it was chosen and its dimensions were edited as it shown in figure 5.38.

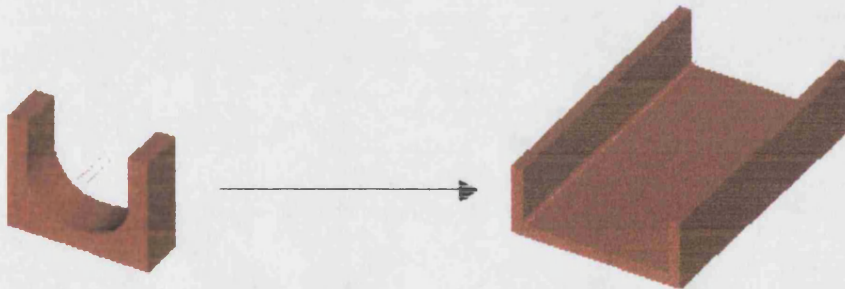


Figure 5.38: The basic feature and the developed shape

The combination of three plates could also be used for the development of the sub-parts B4, B5, B6 and B7. Figure 5.39 shows the basic feature and edited shape for using as the sub-parts B4 and B6

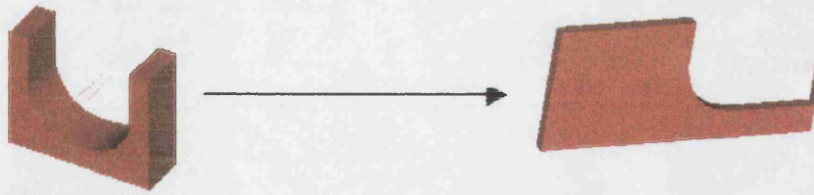


Figure 5.39: Editing the basic feature and creating the necessary sub-part for the product

Step 3: Adding and joining the sub-parts

To develop the product, the edited features need to be joined. The joining process is an easy task in Ideas design software, and could be performed using the following steps:

- Step 1: Click on the join icon
- Step 2: Select a planar surface from the movable feature
- Step 3: Select a planar surface from the first feature to join
- Step 4: Specify a position for joining the features

Figure 5.40 shows the joined sub-parts of the product using these stages.

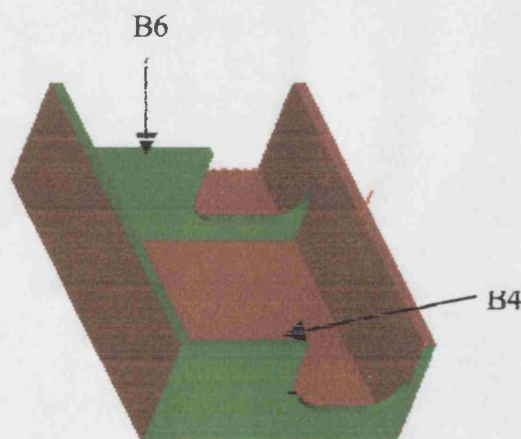


Figure 5.40: The view of the joined features

The process of selecting features, editing and joining, needs to be continued to cover all necessary features of the product. This process is summarized below.

1- Using the combination of a rectangular plate and a positive half cylinder feature (see section 5.5.13) and editing it, creates the sub-part B9 as shown in figure 5.41.

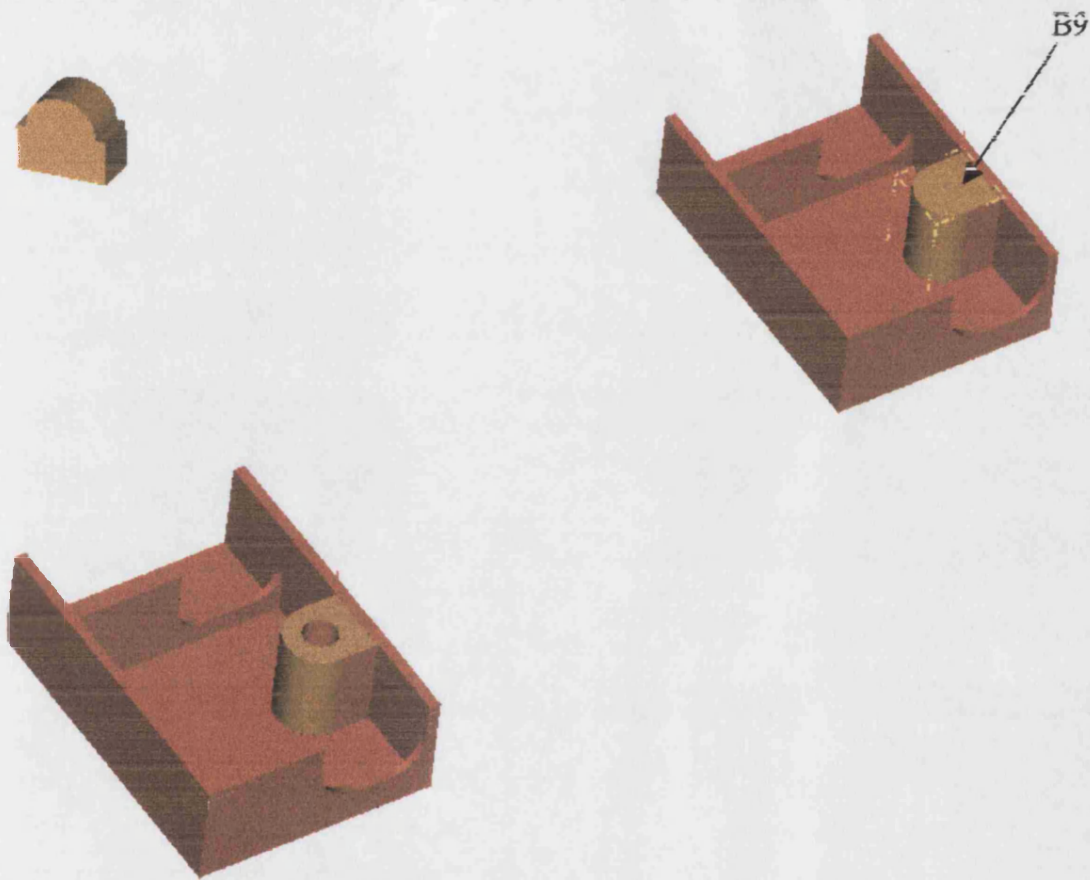


Figure 5-41: Creating and adding sub-part B9

2- Using the wedge feature (see 5.5.4) and editing it creates the sub-part 19, as shown in figure 5.42

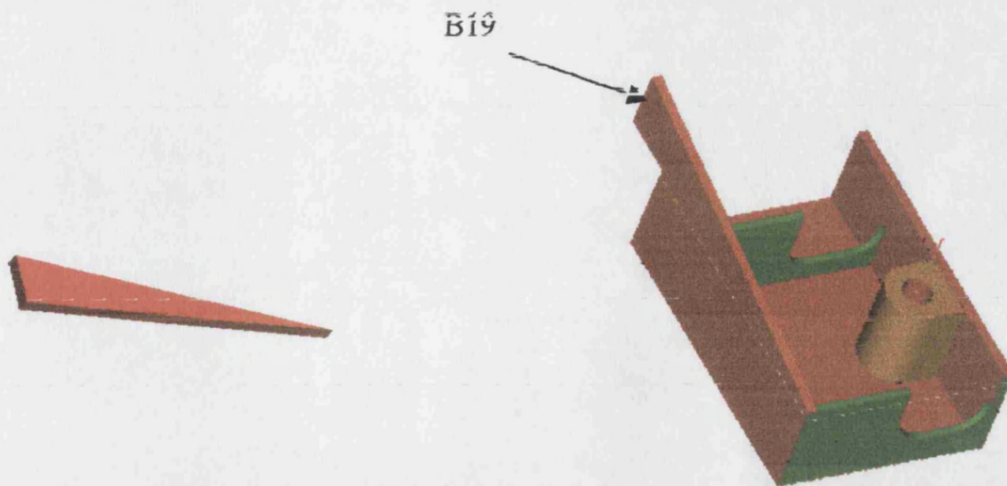


Figure 5-42: Creating and adding sub-part 19

3- Using the cylindrical feature (see 5.5.2) and editing it produces sub-parts 11 and 12, as it shown in figure 5.43.

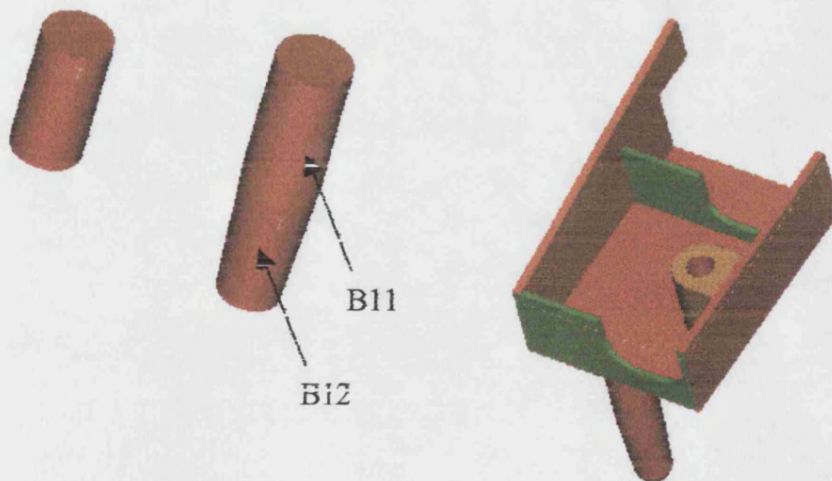


Figure 5-43: Creating, editing and adding sub-parts 11 and 12

4-Using the combination of the three rectangular plates feature and editing it, creates sub-part 7 of the product, as shown in figure 5.44.

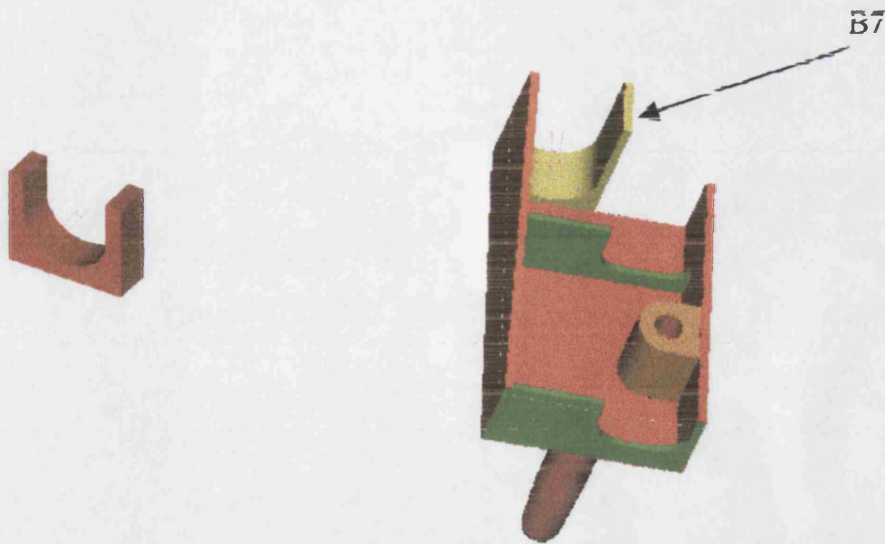


Figure 5-44: Creating and adding sub-part 7

5- Using the combination of the three rectangular plate feature (see 5.5.14) and editing it, creates sub-part 10 of the product, as shown in figure 5.45.

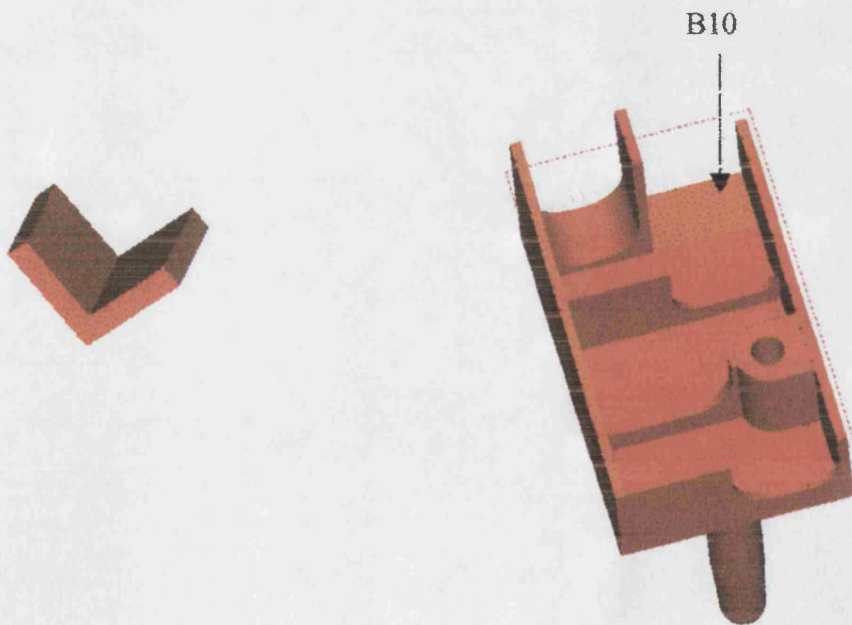


Figure 5-45: Creating and adding sub-part 10

6- Using the combination of the three rectangular plates feature (see 5.5.14) and editing it, creates sub-part 5 of the product, as shown in figure 5.46.

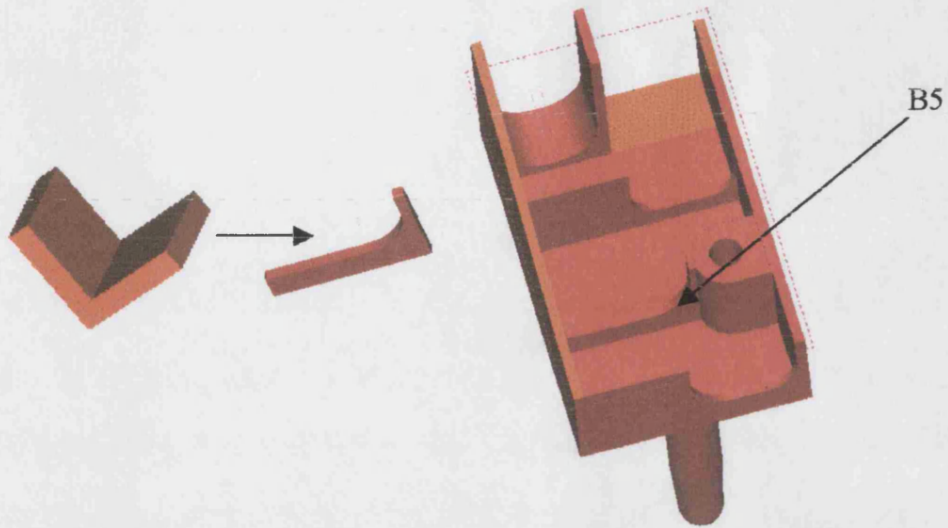


Figure 5-46: Creating and adding sub-part 5

7- Using the rectangular plate feature (see 5.5.1) and editing it produces sub-part 20, as shown in figure 5.47.

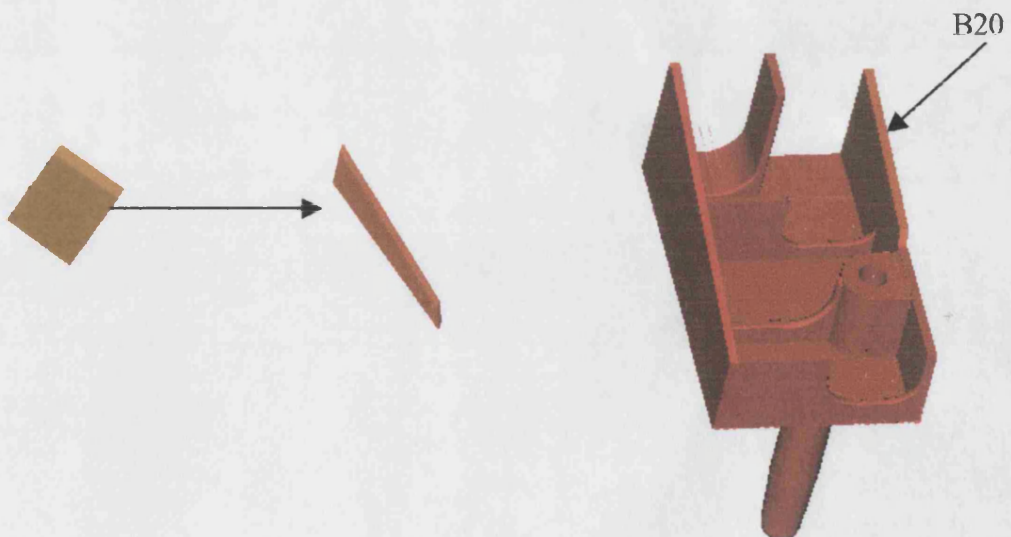


Figure 5-47: Creating and adding sub-part 20

8- Using the rectangular plate feature (see 5.5.1) and editing it produces sub-part 21, as shown in figure 5.48.

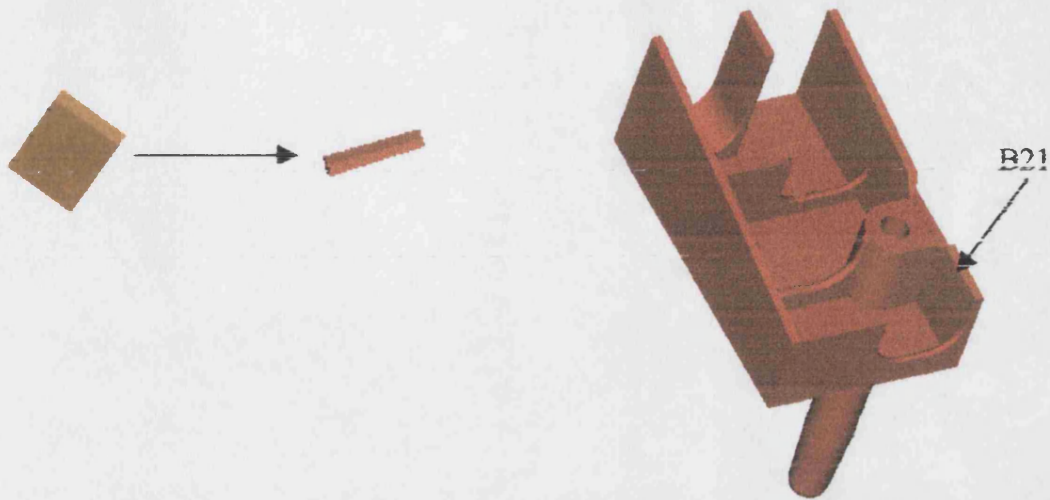


Figure 5-48: Creating and adding sub-part 21

9- Using the rectangular plate feature (see 5.5.1) and editing it to produce the sub-parts 17 and 18 as shown in figure 5.49.

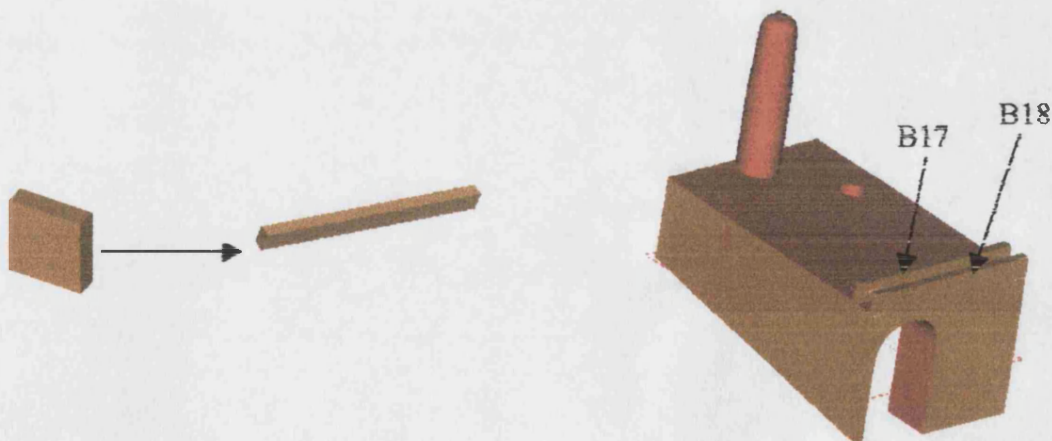


Figure 5-49: Creating and adding sub-parts 17 and 18

10- Using the rectangular plate feature (see 5.5.1) and editing it produces sub-parts 8, 13, 14, 15, and 16 and adding them to the product, as shown in figure 5.50

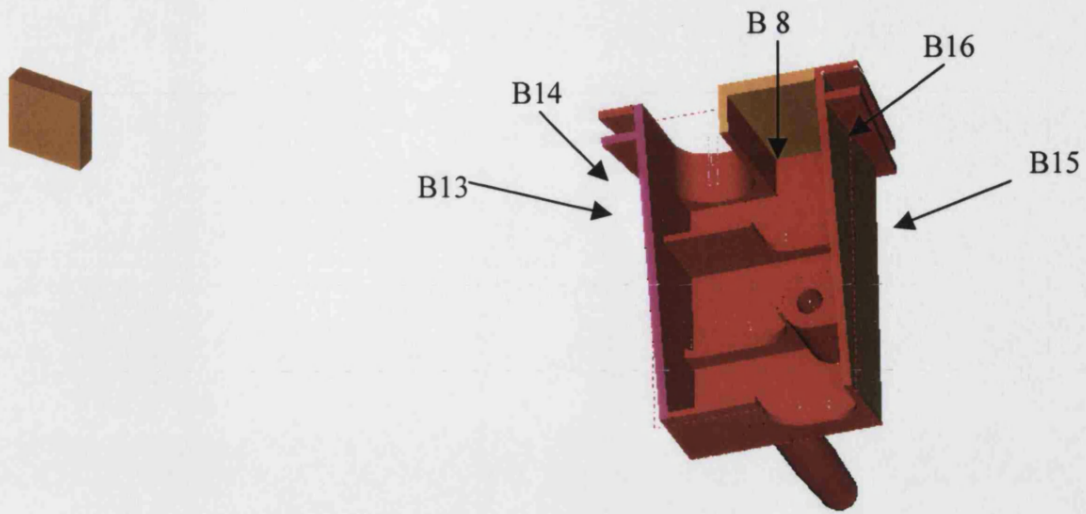


Figure 5.50: Creating and adding sub-parts 8, 13, 14, 15, and 16

Step 4: Editing the developed product

As described in 4.11 a fillet radius between 0.508 and 0.762 mm is necessary to reduce cracking due to notch sensitivity. These necessary changes are assumed to be performed during this stage. However they could be performed during either the sub-parts development or after the joining process. Figure 5.51 shows some necessary fillets on the sub-parts of the product.

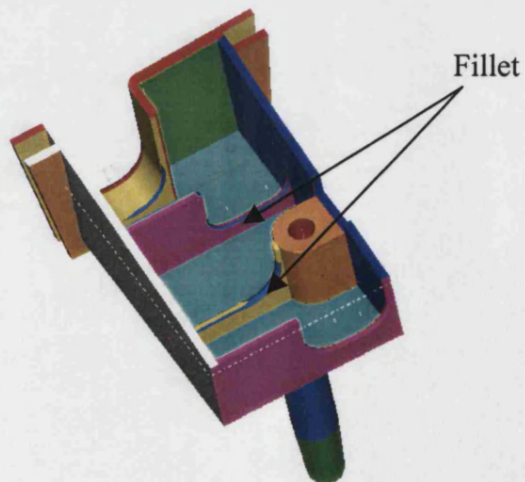


Figure 5.51: Necessary corner fillets for injection moulded product

As illustrated previously, this product can be developed using five basic features, namely; a rectangular plate, a cylinder, a wedge, a combination of rectangular plate and positive cylinder, and a combination of three rectangular plates. However some of these basic features such as the rectangular plate and wedge have been used more than one time. The same procedure has been applied for the other fifty injection moulded products (figure 5.1) and the result are summarised in table 5.1. This table illustrate how the author determined the key feature required for this research.

Table 5.1: The numbers of the basic features found in analysed injection moulded products
















Basic Product number															
1	6		2												
2	3		6		3										15
3	5	2			2								2		
4	1		6	8											2
5	22	2	3	7	4								1		
6	4	3			6			1							6
7	12	1	6		2										
8	1	1			1										2
9			2					2							2
10	2	2			4										4
11															1
12	6		1	3						3					
13	7				2								2		2
14	3				1			1							

Table 5.1: (continue) The numbers of the basic features found in injection moulded products analysed

15			2															
16	2	2		3	2					2								
17	1	1	7							1	1				1	1	3	
18	2	2					3							1	4	2		
19	6	2									1			1	7	4		
20	1	3	1	1				1							2	11		
21	2	1							2		3						16	5
22	1	2												10		1		
23			12				2		1									2
24	3	3																
25	5	3																
26	3	2				4						1						
27	1							2						11				1
28					3						2						17	
29	6	3					2				4				1	11		
30	3				5												5	
31	3	4	2											1		8	1	
32	1	7	1											5	4	2	1	
33	1	13	5						1	1								
34	1		2											8				
35	6	1													6		1	
35		4	1	1											3		1	
37	6	1	3	1											1			
38	4		2											7		11		

Table 5.1: (continue) The number of the basic feature were found in injection moulded products analysed

39	3	2	3														1			
40			7	3	2															
41	1				7				1								2	1		1
42			1	3					2								1	4	1	
43		1						3				8	3				1			
44		3	1	1														1		
45	2	3							2								1			14
46	1						3		2									1		11
47	2	1							4	1								1		1
48	4		16	5	1													2	7	1
49	9	2	1	1														1	1	1
50	2	4	12		4												3	4	1	

Table 5.2 shows the total of each of the features found in the fifty products. This illustrates the reason for the features being built into the cost estimate program. Once the features were identified and classified the next phase was to integrate this to give concurrent cost estimation.

Table 5.2: The total numbers of the basic features found in analysed injection moulded products

																
150	80	102	37	49	7	10	3	19	3	23	5	0	55	47	128	29

Chapter 6

Concurrent Cost Estimation

6.1 Introduction

The cost of producing a product is one of the critical points that the designer should always keep in mind, as this, could be the only reason for the customer not to buy the competitor's product. It could be the main economic feature next to technical features such as quality, size, and other attributes that characterize products. As described in chapter one, the largest part of the product cost (up to 75%) is determined at the conceptual stage of design. This makes good conceptual cost estimation and analysis very advantageous.

For a cost estimation to be made simultaneously with part construction, at the conceptual stage of design, it is necessary to provide tools, which enable the designer to see the result of a design activity on the product cost, during the design process. The design activity can be a change of dimension of the product, adding and cutting features, or changing the material.

A new approach of concurrent cost estimation for injection moulded products is described in this chapter. The approach links design activities and cost estimation techniques, to provide a concurrent cost estimation.

6.2 Cost estimation process

Figure 6.1 shows a flowchart illustrating the cost estimation approach, functions and their relationships, proposed by the author for the concurrent cost estimation system.

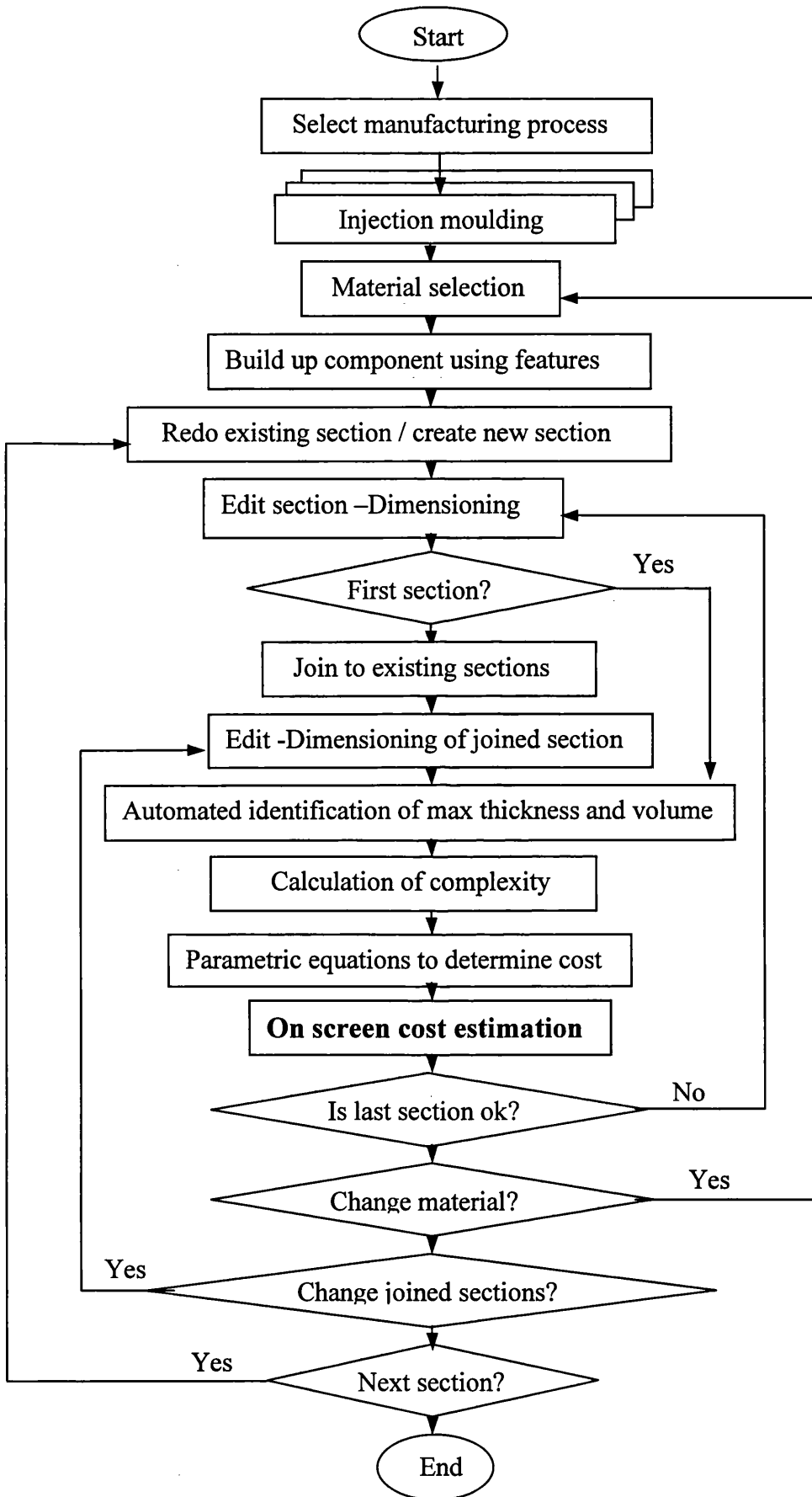


Figure 6.1: The flow chart of the proposed concurrent cost estimation

The following steps are considered:

- 1- Manufacturing process selection
- 2- Injection moulding
- 3- Material selection
- 4- Injection moulding product build using generic features
- 5- Editing dimensions or feature of the sections
- 6- Joining Process
- 7- Editing joined sections
- 8- Automated identification of maximum thickness and volume
- 9- Calculation of complexity
- 10- Cost estimating
- 11- On screen cost estimation

The first seven steps of this flowchart have been described in chapters 4 and 5. However, the material selection is described in greater detail in this chapter because of its significant influence on the product cost.

6.2.1 Material selection

Material selection is one of the most important factors in the product design process [Giachetti, 2001]. In many cases the material influences manufacturing equipment, cost and product characteristics. A methodology is required to help the designer select the most appropriate material for new products. Dieter [1988] states that a material selection methodology needs four steps to be performed. The first step is to identify the material requirements for the product. The selected material should function properly in the service conditions required for the product. The second step is to filter the materials by comparing the requirements of the product

and the properties of the material. This would eliminate materials that do not have the required properties. The third step is to select the candidate materials by comparing the performance, cost, manufacturing process required and the availability of each material. Finally, the fourth step is to test the selected material in a simulated environment to determine whether the material functions properly in use.

Ashby [1992] developed another method of material selection. In his method, the materials are categorised into six primary classes, which are metals, ceramics, glasses, plastics, elastomers and composites. Metals are subdivided into aluminium alloys, copper alloys, lead alloys, magnesium alloys, molybdenum alloys, nickel alloys, steels, tin alloys, titanium alloys, tungsten alloys, and zinc alloys. Ceramics are subdivided into alumina, diamond, sialons, silicon carbide, silicon nitride and zirconia. Glasses are subdivided into borosilicate, soda and silica. Plastics are subdivided into epoxies, melamines, polycarbonates, polyesters, polyethylene, high-density polyethylene, poly formaldehyde, polymethylmethacrylate, polypropylene, polytetrafluorethylene, and polyvinylchloride. Elastomers are subdivided into natural rubber, hard rubber, polyurethanes, silicone rubber and soft butyl rubber. Composites are subdivided into carbon fiber reinforced polymer, glass fiber and Kevlar fiber.

Ashby has developed material property charts to determine the material that may be selected for a particular design. His method uses the relationship between properties to determine which group of material may be used for the design. For example, the strength-relative cost chart plots the modulus of strength of a material against its relative cost. The cost of the material per kilogram divided by the cost per kilogram of mild steel rod is a relative cost. The performance ratio for a beam is $C = \sigma / C_R \rho$

where σ is the strength, C_R is the relative cost, and ρ is the material density. The performance for plate is $C = \sigma^{1/3} / C_R \rho$, and is $C = \sigma^{1/2} / C_R \rho$ for a column.

The relationship is represented as a line on the chart. Materials that lie on the line perform equally well in that particular design application. Material that lie above the line perform better in the design application and materials that lie below the line do not perform as well as those on or above the line.

Based on the materials property chart described above, Ashby has developed a software package called the Cambridge Material Selector (CMS). The package consists of 167 materials and their detailed properties and attributes. The first stage in using the package is the selection of the desirable range for material property (figure 6.2). The software then filters the database for any material that meets the given criteria and shows the material in a window. The user can decrease the list by applying additional constraints until one material is selected. The limitation of this software is that this method is a material based method and the process selection is not considered.

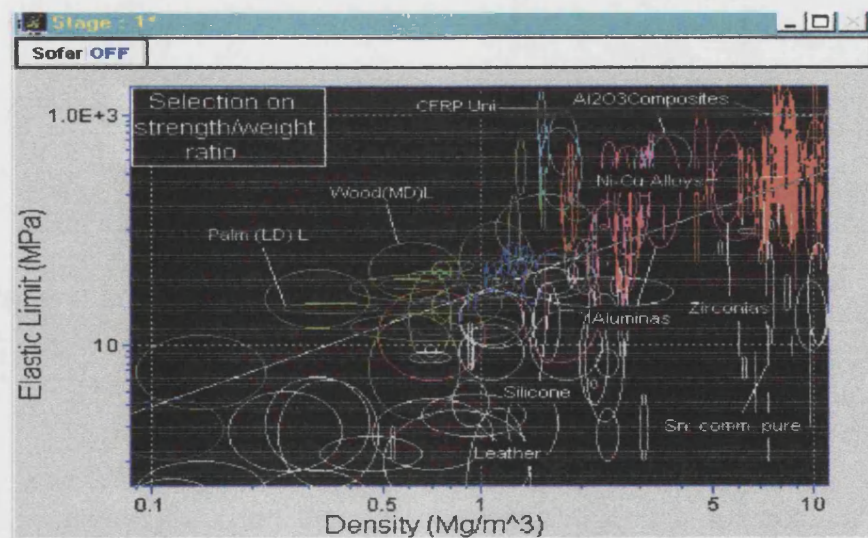


Figure 6.2: The first stage of CMS package [CMS, 2002]

A material database for injection moulded products has been developed by the author of this thesis to use during the design process. This database contains 30 injection moulding materials and their properties. However, it is assumed that the selection of the material has already been performed or restricted to a few materials only. Hence, the designer need only choose the selected material from the provided material database (figure 6.3) for the cost estimation process.

In the proposed method of cost estimation, a new material file is created for each product design. When a material has been chosen, all material information such as density, price, and scrap rate are transferred from the material database file into the new product material file. This information is then used for the cost estimation process. To enable the designer to see the effect of the different materials on the product cost, the material database, can be accessed again, during the design process. If a change in the chosen material has been specified, the new material specification will be added to the product material file, and will be used for the calculation of the cost, for the next stages of the cost estimation process. The product material information can be saved and printed when needed.

Material Name	characteristics:	Density(g/mm3)	Price(£/g)	Scrap rate%	Thermal di	Melt temprature(0C)	L_melt_tem
ABS	Hard and rigid. Good chemical resistance	0.001040	0.00100	0.0500	0.128	238.000	45.000
ACRYLIC	Consistant mechanical properties. low def	0.001180	0.02350	0.0500	0.350	180.000	169.000
ERTALON 6 XAU	Cast nylon offering the possibility of manuf	0.001135	0.06300	0.0500	0.280	220.000	165.000
ERTALYTE	High mechanical strength, stiffness and ha	0.001410	0.07200	0.0500	0.200	116.000	99.000
NYLON 101	High stiffness and creep resistance even	0.036000	0.02500	0.0500	0.223	255.000	200.000
PC	It has excellent strength and toughness. It	0.001200	0.03000	0.0500	0.210	137.000	128.000
PEEK	High mechanical strength, stiffness and ha	0.001320	0.37200	0.0500	0.250	160.000	88.000
POLYPROPYLENE	An extreme resistance to chemicals and e	0.000850	0.01350	0.0500	0.200	173.000	122.000
PTFE	Outstanding chemical resistance whit sup	0.002150	0.02150	0.0500	0.250	327.000	273.000
PVC Type 1	Its flexible grades are easy to process. Its	0.001360	0.01100	0.0500	0.140	96.000	78.000
PVDF	An outstanding thermoplastic material whi	0.001780	0.19230	0.0500	0.170	169.000	80.000
TORLON 4301	Outstanding strenght and creep resistance	0.001439	0.35000	0.0500	0.170	278.000	205.000
VESPEL	Does not melt or soften even at 480 degre	0.001510	0.08500	0.0500	0.400	360.000	260.000
UPE/PAK	A high impact polycarbonate based mate	0.001270	0.01500	0.0500	0.170	81.000	80.000

Figure 6.3: Snap-Shot of Material Database for Injection Moulding

6.2.2 Automated identification of the product volume and maximum wall thickness

The product volume and maximum wall thickness are other key factors in estimating the cost of injection moulded products. The volume of the product, directly influences material cost, and the product maximum wall thickness, directly effects the products cooling time which in turn influences the production cycle time. The product volume and maximum wall thickness are described separately in the following sections.

6.2.2.1 Automated identification of the product volume

The weight of the injection moulded product is necessary for the calculation of the material cost. The weight of the product could simply be calculated using the volume of the product multiplied by the density of the material. Therefore, the product volume is a necessary first step for the calculation of its weight. In addition, the volume of the product is a main factor for the shot capacity of the injection moulding machine that affect the processing cost.

Depending on the product complexity and its geometry, calculating the product volume manually can be difficult. However, in the proposed method of product development, the designer deals with a series of simple features during the design process. This can simplify the volume calculation, enabling the designer to benefit from the automatic calculation of the products volume.

In virtually all of today's CAD packages, the calculation of product volume can be carried out automatically. For example, in Ideas, it is possible to calculate the product volume by using the product properties and the volume calculation

icons. The calculated volume can then be seen on the screen and can be saved to various output files.

To provide an automated identification of the product volume for the cost estimation process, the Ideas output file with the default name "INFO.DAT" has been used. However the user can change this name during the design process. This file is a system specified format file and contains much information with a sub-set of this being used during the cost estimation process. The author has developed a FoxPro programme to filter the Ideas output file and access the information necessary for the cost estimation process. This programme continually checks the Ideas output file, and if a change occurs, the filtration process is repeated. In other words, during the design process, any change in the volume and dimensions of the product, will be captured automatically, filtered, and then used during the cost estimation process.

6.2.2.2 Automated identification of the product maximum wall thickness

As well as the product volume, the product cooling time, as described in chapter 1, is another of the main cost factors for injection moulded products. There are several different formula (Equation 6.1 to 6.3) for the calculation of the cooling time for injection moulded products. The majority of these are based upon the general principal that cooling time increases in relationship to almost the square of the maximum wall thickness. This shows the importance of wall thickness to the cost of injection moulded products. Equation 6.1 was suggested by Linder [1985] for the calculation of the cooling time:

$$\text{Cooling Time (s)} = \frac{t^2}{2\pi X} * \ln \left(\frac{\pi * (T_m - T_w)}{4 * (T_e - T_w)} \right) \quad \text{Equation 6.1}$$

Where: T_m = Melt Temperature (° C)
 T_w = Mould Temperature (° C)
 T_e = Demould Temperature (° C)
 X = Thermal Diffusivity (mm²/s)
 t = Thickness (mm)

The following formula (equation 6.2) was suggested by Fenner for the calculation of the cooling time [Fenner, 1979].

$$h^2 = \frac{2 k_s t}{\rho_s \lambda} (T_m - T_b) \quad \text{Equation 6.2}$$

Where: T_m = Melting Temperature (°C)
 T_b = Temperature of Cavity Boundary (°C)
 ρ_s = Density (Kg/m³)
 K_s = Thermal Conductivity of solid skin (W/m⁰C)
 λ = Latent Heat of Fusion (Kj / Kg)
 t = Time (s)
 h = Thickness (mm)

The following formula (equation 6.3) was suggested by Bernhardt for the calculation of the cooling time [Bernhardt, 1960].

$$t = \frac{-\alpha^2}{4.24 \alpha'^2} (\text{Log } \theta - \text{Log } 0.81) \quad \text{Equation 6.3}$$

Where: α' = Thermal Diffusivity

t = Time Variable

a = Thickness

$$\theta = \frac{T_t - T_m}{T - T_m}$$

Where: T_t = Polymer Temperature at any time t ($^{\circ}\text{C}$)

T_m = Mould temperature ($^{\circ}\text{C}$)

T = initial Polymer temperature ($^{\circ}\text{C}$)

Although, these equations indicate that the products should be designed with the minimum wall thickness in order to minimise the cooling time, the products functional strength requirements and mould filling considerations are also important. In practice, the maximum wall thickness of a well-designed injection molded product normally ranges from, 2 mm to 4 mm. However a wall thickness greater than 4mm can be used in exceptional circumstance.

It is at the conceptual stage of design that a change to the maximum wall thickness could be most easily applied, but no published method has been found in the literature, which examines the automatic identification of maximum wall thickness. It is the author's experience that this is a key factor when examining conceptual cost estimation.

For a fabricated component, there are several methods of determining the maximum wall thickness. For example, the ultrasound method of thickness measurements has

been used for many years [Rolf, 1995]. Via this method, it is possible to measure the thickness of walls that are accessible from one side only. In addition, with this method large-scale non-destructive control of a containers wall thickness can be realised.

In this research, a method of wall thickness identification has been developed that enable designers to keep a check on the maximum wall thickness as they design an injection moulded product. As described, a FoxPro program has been developed for filtering and transferring the thickness information from Ideas into the cost estimation program during the design process. Figure 6.4 presents the flowchart diagram of the program for determining concurrent the maximum wall thickness. It contains the following steps.

Step 1. Import the Ideas output file

As mentioned in section 6.6.2.1 the design information can be sent into an Ideas output file that is named INFO.DAT by the system. This file is checked continually enabling current design data to be assessed.

Step 2. Creating INFO.DBF

To capture the design data in the FoxPro program, the format of the INFO.DAT, needs to be changed from a text file to a database FoxPro format file to enable data manipulation. This file is named "INFO.DBF".

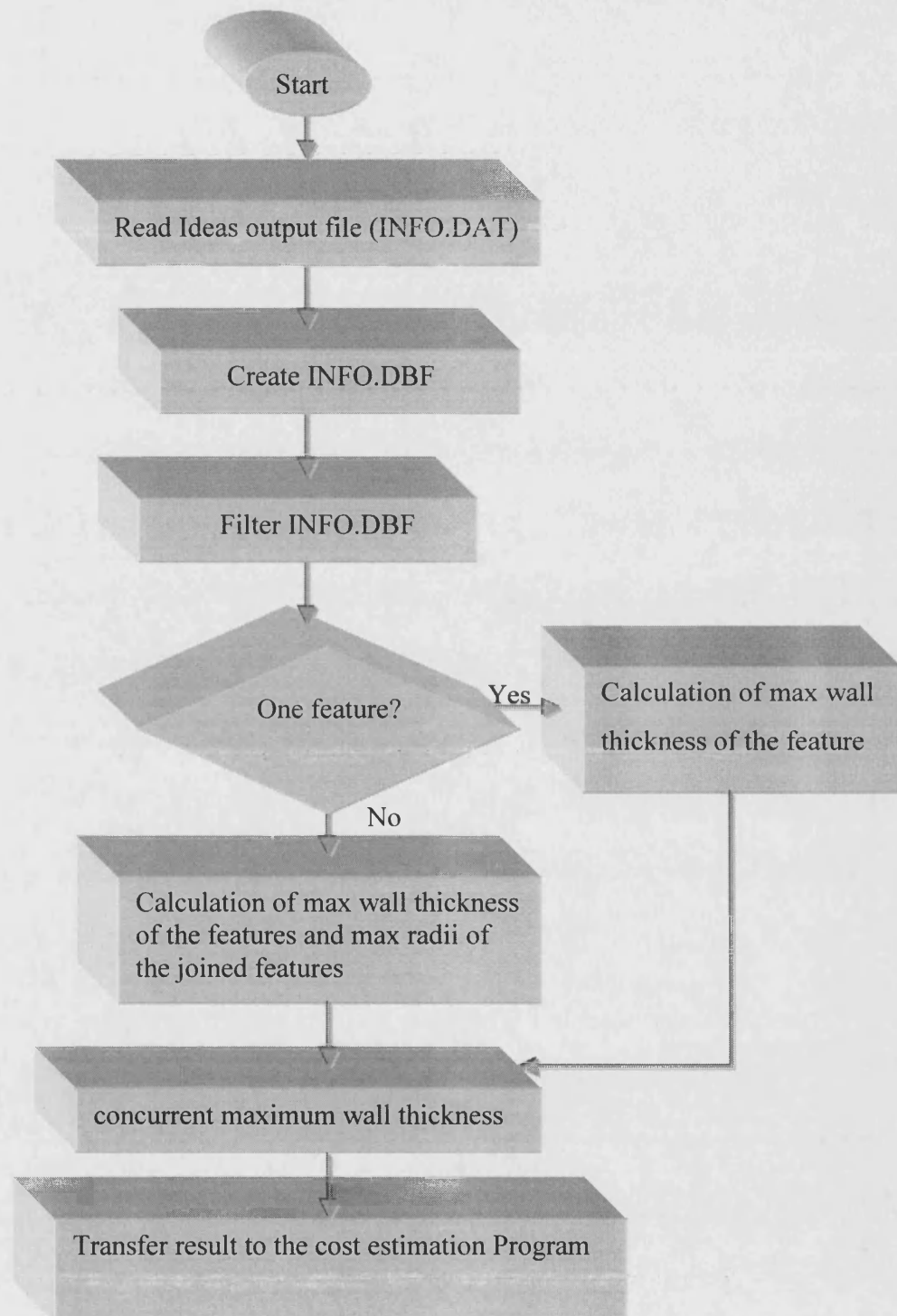


Figure 6.4: The flowchart depicting maximum wall thickness calculation

Step 3. Filtering the INFO.DBF

Ideas exports a large amount of design information into its output files and most of this is not required for the wall thickness calculation. Therefore, the information needs to be filtered to provide only the information necessary for the wall thickness calculation and cost estimation process. Another benefit of this filtration is that it creates a relatively small database file that more readily facilitates the data searching and processing required. The filtered information is then stored in a FoxPro database file that is named “DIMENSION.DBF”. The maximum wall thickness is then extracted from this file, using step 4.

Step 4. Maximum wall thickness calculation

To calculate the product maximum wall thickness, the product dimensions and the information about the joint features is transferred into the ideas output file. This is an easy task, through the selection of all the feature dimensions and joint information using the “info” icon in the Ideas software.

As mentioned in chapter 5, in the proposed methodology of building up a product feature by feature, the features are chosen individually and are then joined. Therefore, the maximum wall thickness of the first feature chosen will be the minimum value of its X, Y, Z dimensions, as shown in equation 6.4.

$$\text{Max Wall Thickness (MWT)} = \text{Min [feature dimensions]}$$

Where

Feature dimensions > 0

Equation 6.4

After the second feature has been added to form a “T” joint, the maximum wall thickness could be considered as the minimum thickness of the first or the second feature or more correctly the maximum thickness where the two features join. For example the maximum thickness for the product shown in figure 6.5, will be as given in equation 6.5 and is equivalent to the diameter ”D” of the largest included circle that can be fitted into the joint.

$$\text{MWT} = \text{MAX} \{ \text{Min (Dimensions feature 1)}, \text{Min (Dimensions feature 2)}, \text{diameter of the joined section} \}$$

Equation 6.5

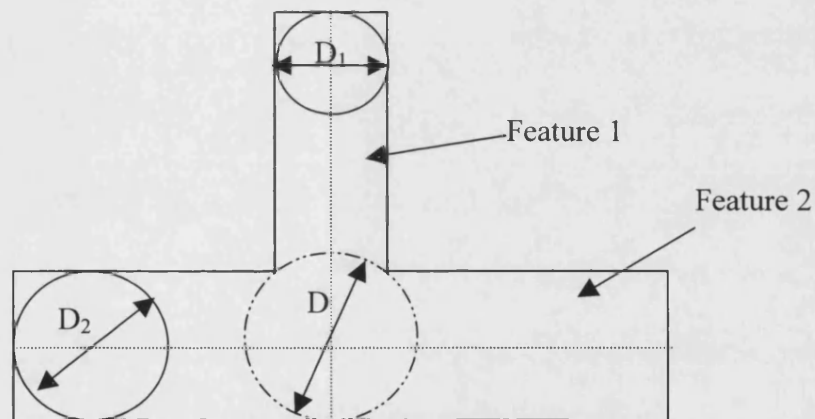


Figure 6.5: The maximum thickness D of two “T” joined features

Where

D₁ = The diameter of the largest included circle of feature 1

D₂ = The diameter of the largest included circle of feature 2

D = The diameter of the largest included circle of the joint feature 1 and feature 2

D_2 = The diameter of the largest included circle of feature 2

D = The diameter of the largest included circle of the joint feature 1 and feature 2

The radius of the included circle for the two joined features, can be calculated using the following equation:

$$R = \frac{(R_1)^2}{4R_2} + R_2 \quad \text{Equation 6.7}$$

$$\text{Maximum wall thickness} = 2R$$

Where:

R_1 = the radius of the maximum included circle of feature 1

R_2 = the radius of the maximum included circle of feature 2

A similar rule could be applied for the calculation of the maximum wall thickness after the next feature has been added to the product. Figure 6.6 shows a three-dimensional shape with three joined features.

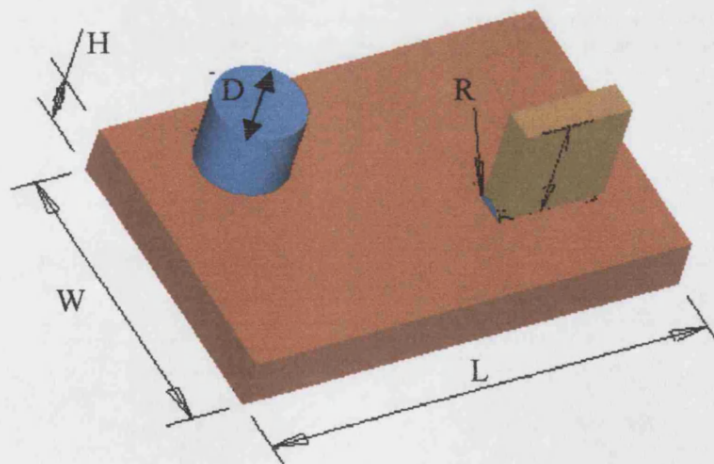


Figure 6.6: The maximum thickness of joined features

Therefore:

$$\text{Product Max Wall Thickness} = \text{Max} \{ \text{Min} (LWHD)_i, \text{Max} (2R_j) \}$$

When L, W, H, D > 0

Equation 6.6

Where:

i = The specified number of the feature, (i = 1,2,...all selected features)

j = The specified number of the joined features, (j = 1,2, ..., all joined features)

L = The length of the feature

W = The width of the feature

H = The height of the feature

D = The diameter of the feature

R = The radius of the joined section

If two features form an “L” joint (see figure 6.7) then the largest section thickness is equivalent to the largest included circle that can fit into the joint. This can be calculated using equation 6.8.

$$R = (2R_1 + 2R_2 - \sqrt{8R_1R_2}) \quad \text{Equation 6.8}$$

$$\text{Maximum wall thickness} = 2R$$

Where:

R₁ = The radius of the maximum included circle of feature 1

R₂ = The radius of the maximum included circle of feature 2

R = The radius of the maximum included circle of joint

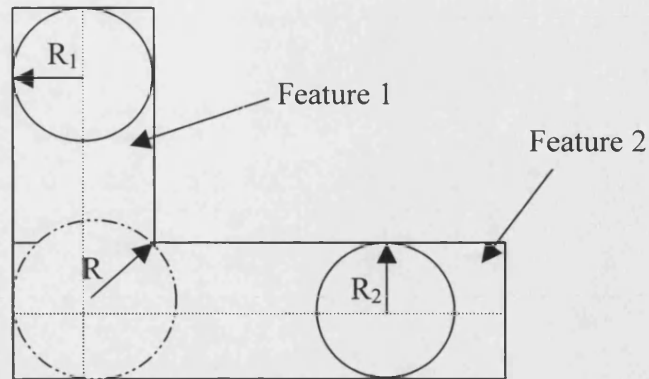


Figure 6.7: The maximum thickness ($2R$) of two “L” joined features

In practice, sharp corners need to be radiused (figure 6.8) for injection moulded products, as they increase the stress concentration. In such cases the radius (r) used to blend two features has the effect of increasing the size of the included circle such that, its radius can be calculated using equation 6.9.

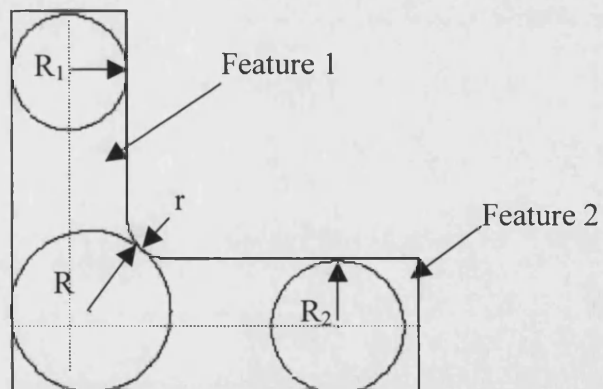


Figure 6.8: The maximum thickness ($2R$) of two blended “L” joined features

$$R = \left(3r + 2R_1 + 2R_2 - \sqrt{8r^2 + 4r(2R_1 + 2R_2) + 8R_1R_2} \right) \quad \text{Equation 6.9}$$

Maximum wall thickness = 2R

Where:

R_1, R_2 = the radii of the included circles of feature 1 and feature 2

r = the blend radius of the circled corner

R = the radius of the maximum included circle of the blended “L” joint

Likewise, the maximum wall thickness of two “T” jointed features such as figure 6.9, with blend radii, can be calculated using equation 6.10.

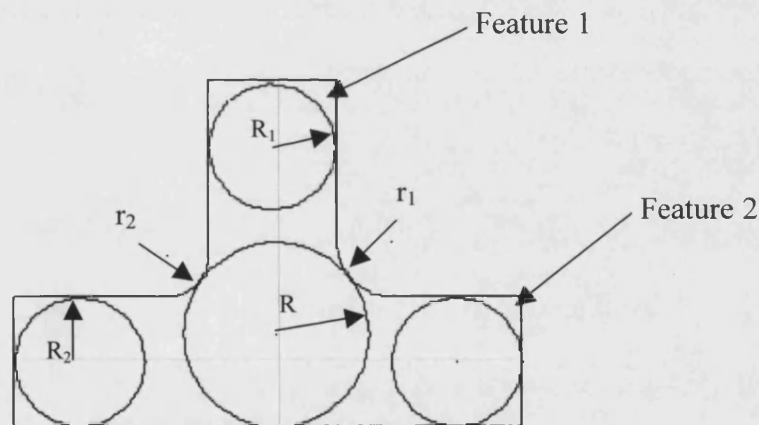


Figure 6.9: The maximum thickness (2R) of two blended “T” jointed features

$$R = \left(\frac{(r_1 + r_2 + 2R_1)^2 + 4R_2(r_1 + r_2 + 2R_2 + 2\sqrt{(r_1 + R_2)(r_2 + R_2)})}{4(r_1 + r_2 + 2R_2 + 2\sqrt{(r_1 + R_2)(r_2 + R_2)})} \right)$$

Equation 6.10

Maximum wall thickness = 2R

Where:

R_1, R_2 = the radii of the included circles of feature 1 and feature 2

r_1, r_2 = the radius of the two blends

R = the radius of the maximum included circle of the blended "T" joint

The mathematical calculation for three features joined as a blended double "T" is shown in figure 6.10.

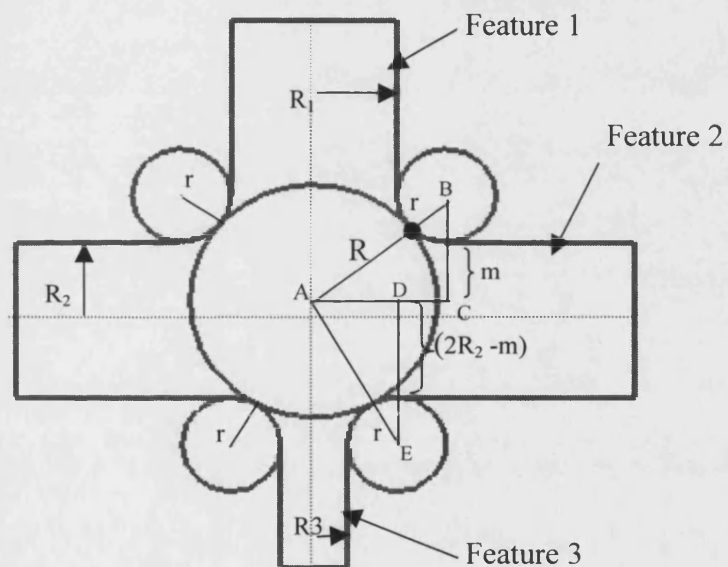


Figure 6.10: The maximum thickness ($2R$) of 4 joined features with blends

Assume;

R_1, R_2, R_3 = the radii of the included circles for features 1, 2, 3, and 4

r = the radius blend

m = the distance that are shown in figure 6 9

R = the radius of the maximum included circle of four joined features with blends

It is clear from the triangle ABC that using Pythagoras:

$$(R + r)^2 = (r + m)^2 + (r + R_1)^2$$

Also from the triangle ADE it is clear that:

$$(R + r)^2 = (r + (2R_2 - m))^2 + (r + R_3)^2$$

Therefore:

$$(r + m)^2 + (r + R_1)^2 = (r + (2R_2 - m))^2 + (r + R_3)^2$$

And,

$$m = \frac{4rR_2 + 4R_2 + (r + R_2)^2 - (r + R_1)^2}{4(r + R_2)}$$

Hence,

$$R = \left(-r + \sqrt{\left(r + \left(\frac{4rR_2 + 4R_2 + (r + R_2)^2 - (r + R_1)^2}{4(r + R_2)} \right) \right)^2 + (r + R_1)^2} \right)$$

Equation 6.11

Maximum wall thickness = 2R

The radius of the maximum included circle of any joined section with or without blends can be calculated using similar procedures. The radius of the maximum included circle of the corners of three joined sections in 3D, considered to be the maximum included circle of the two thicker sections. However in this research only equation 6.11 has been used as an example for the calculation of the maximum thickness of the three joined features and in the case of different blend radii the maximum radius has been used in the calculation.

6.2.3 Calculation of Complexity

As described in chapter 5, the proposed design process of an injection moulded product starts with the selection of one basic feature such as a plate or a cylinder. Such a feature is simple and non-complex. As the process of the product design proceeds, and other features are added, the complexity of the product increases. For the purpose of this research the complexity is assumed to be a function on the following parameters that could evidently affect product cost.

1. General shape

General shape of the product could have an effect on the required mould and injection machine selection.

2. Maximum product wall thickness

The main effect of the wall thickness could be on the product cooling time.

3. Volume of the product

The volume could affect the mould and the cycle time.

4. Tolerance and surface finish

The required tolerance and surface finish could affect the mould and the material temperature that in turn will affect the product cycle time.

All of these parameters influence the product cost directly and therefore, need to be included in the cost estimation process.

In the proposed cost estimation methodology, some of these parameters such as volume and dimensions could be deduced automatically, from the Ideas software, during the design process. But parameters such as the machine size and the mould information are entered manually. Table 6.1 shows the necessary information for the proposed cost estimation process. Some of this information is used for the product complexity.

Necessary information	Description	Type	Can be use for
Dimension	Length, width, height, radius, joined sections	Automated	Max wall thickness calculation
Volume	Volume of a feature or volume of a joined features	Automated	Cost of material-mould and machine required
Material	Type, price, density, scrap rate, dry-time, thermal properties	Manually entered, Automated selection	Cost of material
Mould information	Mould temperature, de-mould temperature, lower de-mould temperature	Manually entered Automated selection	Machine size
Product information	Production volume, cross-hole, tolerance, internal thread, Project area	Manually entered Automated selection	Cost of the product

Table 6.1: Manual and automated information necessary for the cost estimation system

The manually entered information need only be entered once and it is then saved into files that can be accessed automatically for the various calculations needed.

The main factors that have been shown to increase the product cost are discussed below.

- Dimensions of the features

The dimensions of the feature are required for the calculation of the product volume and wall thickness. The wall thickness as described before influences the cooling time and product cycle time, which effects the product cost. The general shape of the product impacts on the mould size and complexity.

- Volume

The volume of the product directly affects its weight and therefore influences the product cost.

- Material

The products mechanical specification such as stiffness and impact strength affects the material type required. Each material will have a unique set of moulding parameters and raw material cost that influence the product cost.

- Machine information

The required machine affects the process cycle time and output rate. These helps determine the processing cost.

- Mould information

The number of the parts in the mould, its size, level of automation and the number of cavities all affect the product cost.

- Product information

The number of products required influences the number of cavities in the mould and the machine size, both of which affect product cost.

The information described above, has been incorporated into the proposed cost estimation process through the use of Currie's equations ([Currie 1996], (see chapter 3) and are further described within an example in chapter 7.

6.2.4 Automated cost estimation process

Cost estimates based on the material properties, product dimensions, and the presence of complex parameters are calculated for each step of the product design process and displayed concurrently. As the designer develops the product and the information is sent into the Ideas output file, the cost estimates are shown on the screen. This enables the designer to see the growth of the product cost as it develops with the addition of new features. This could help the designer to edit or delete features, which have been shown to influence the product cost significantly. For example, for a product that is sensitive to changes in maximum wall thickness, a large increase in product cost might be caused by a seemingly insignificant change in the product wall thickness. This sensitivity could be seen and avoided during early product design. Therefore, the proposed methodology not only provides cost estimations during the design phase but acts as an advisory system for the designer to create products with the lowest possible costs.

In addition, information such as product volume, material, maximum wall thickness, weight, and cycle time are shown along with the estimated cost on screen during the design process. This information can be edited manually. Figure 6.11 shows a screen picture of the concurrent cost estimation results. The screen is divided into four sections and the name of each section is shown in the top of the section. The sections consist of:

- 1- Ideas Student Edition (Design).

2-Ideas Icons

3-Ideas Prompt.

These three sections are used for design activities

4- Microsoft Visual FoxPro is used for concurrent cost estimation of the designed product. As it is shown in figure 6.11, the product properties such as volume, weight, wall thickness, etc. are shown in the screen. Also the product estimated cost is shown in this section.

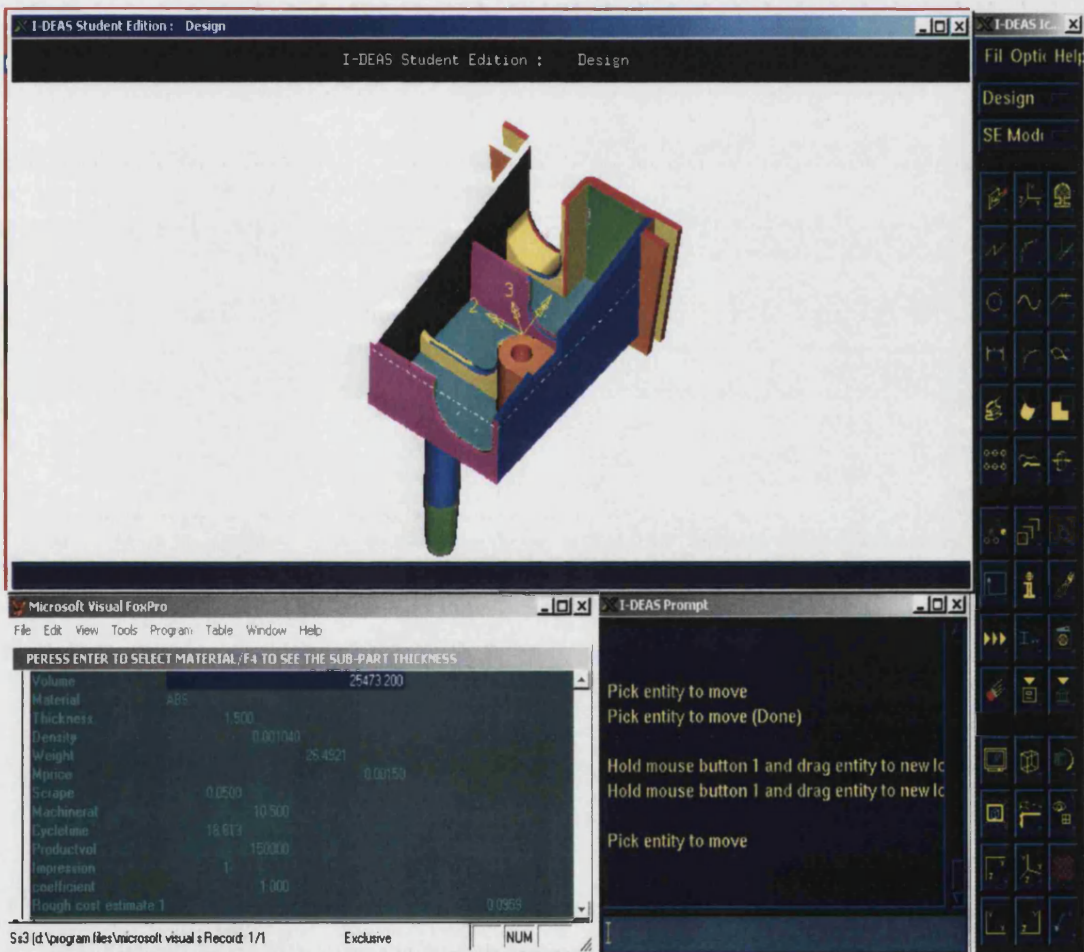


Figure 6.11: The view of the concurrent cost estimation

The process of cost estimation is repeated continually during the design process and the estimated cost for each step can be saved into files. Drawing a diagram of the relationship between product cost and features is also possible (figure 6.12) after the stage of design process has been completed. This possibility is described in greater detailed in chapter 7.

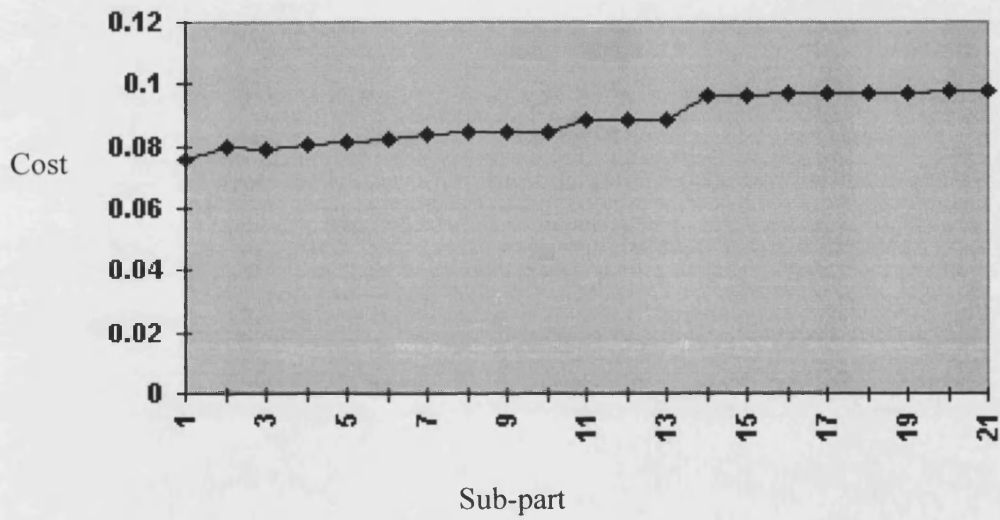


Figure 6.12: The graphical view of the concurrent cost estimation

Chapter 7

Using the cost estimation methodology

7.1 Introduction

In this chapter, a documented step-by-step example of the use of the proposed Injection Moulding Cost Estimating Program (IMCEP) and the data conversions contained within this research are described for an injection moulded product that is shown in figure 7.1. This illustrates the various stages of developing the product and its related cost. The cost estimates were undertaken on a product for which only the conceptual information was available (see chapter 1 section 1.3).

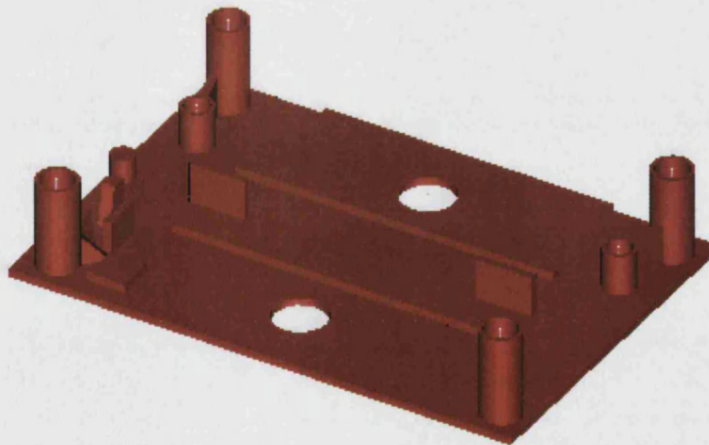


Figure 7.1: The final injection moulded product

7.2 Example of the product cost estimation

To estimate the product cost using the research methodology, it is necessary that the product being designed uses the basic features which were described in chapter 5. Additional information is also required which will be described.

The proposed product can be constructed using four basic features, namely the rectangular plate, the cylinder, the hollow cylinder, and the wedge. The rectangular plate being used 12 times, the cylinder seven times, the hollow cylinder six times and the wedge twice. The 27 developed sub-parts are shown in figure 7.2.

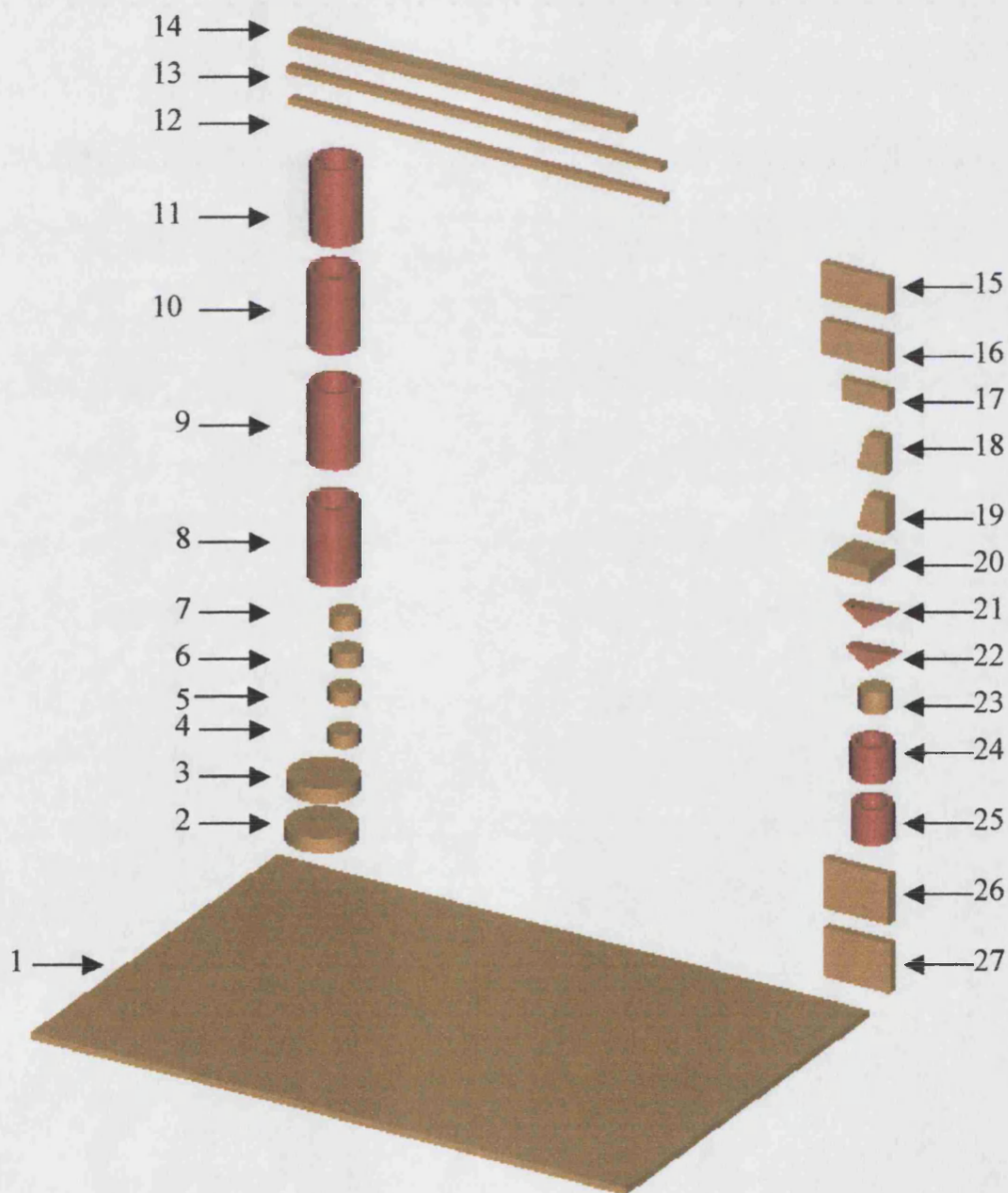


Figure 7.2: The sub-parts of the injection moulded product

7.2.1 Information required for cost estimate

The cost estimation methodology needs seven key areas of information to estimate the product cost. However, most of this information can be obtained as the product is being developed during the design stage and any calculations that are required are done automatically. Each of the steps below are discussed in relation to the sample product and allow a cost estimation to be made progressively as the design is developed and displayed on screen for use by the designer.

- 1- Production volume.
- 2- Projected area for the product.
- 3- Material specification and price per kg.
- 4- Product volume and weight.
- 5- Maximum wall thickness of the product.
- 6- Cycle time, which includes; the dry cycle time, the injection time, the cooling time and any additional time required to produce a tight tolerance, a gloss finish, undercuts, internal threads and/or cross holes.
- 7- Number of impressions.

It is assumed that the following decisions have already been made with respect to the product and entered into the computer program.

Material = Acrylonitrile Butadiene Styrene (ABS)

Production volume =20000/year

The other information required for the cost estimation can be gained using the following procedure.

7.2.2 Projected Area

To develop the product it is necessary that one of the 27 sub-parts being considered be used as the first sub-part. Others are joined later. As a general rule and for this test product, sub-part 1 (figure 7.3) was chosen as the first feature, because it is the largest sub-part. The feature is selected from the Ideas menu, and dimensioned. The dimensions and volume of this sub-part are then transferred from the Ideas design software into IMCEP using the properties icon “I_{xx}” and the information icon “i”. IMCEP calculates the projected area of the sub-part and as a default this is assumed to be derived from the largest of the sub-part’s surfaces. Therefore for this sub-part:

$$\text{The Project Area} = (43 \times 63) \times 2 + 2 \times (2 \times 43) + 2 \times (2 \times 63)$$

$$\text{The Projected Area} = 5842 \text{ mm}^2$$

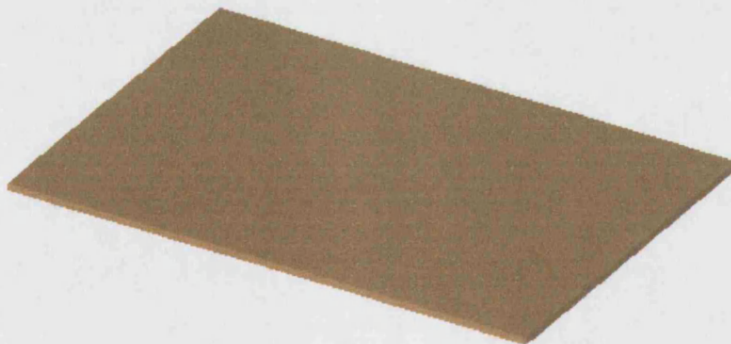


Figure 7.3: The first sub-part of the injection moulded product

7.2.3 Material information

As the ABS is assumed to be the material for the product, the following information can be obtained from the integrated material database.

$$\text{Material price} = \text{£}10.00 / \text{kg}$$

$$\text{Density} = 0.00104 \text{ g/mm}^3$$

Scrap rate = 5%

Melt temperature = 238 °C

Mould temperature = 45 °C

De-mould temperature = 94 °C

7.2.4 Volume and weight calculation

The volume of the sub-part can be transferred directly from Ideas into IMCEP so that the sub-part's weight can be calculated.

Sub-part volume = 5418 mm³

Therefore:

Weight = 5418 * 0.00104 = 5.635 g

7.2.5 Maximum wall thickness calculation

As described in 6.6.2.2 to calculate the maximum wall thickness, as a general rule the maximum wall thickness is the minimum of the X Y Z dimensions. Therefore for the first sub-part it can be calculated as follows:

Sub-part wall thickness= Min (Length, Width, Extrude distance)

Sub-part wall thickness= Min (63, 43, 2)

Product wall thickness = 2mm

7.2.6 Cycle time calculation

The cycle time for injection moulded products can be calculated using the following equation:

Cycle time = Dry cycle time + Injection time + Cooling time + Complexity Additions

The calculation of each of these is described below.

7.2.6.1 Dry cycle time calculation

The dry cycle time is mainly dependent on the component weight and based on the information supplied by the manufactures of the injection moulding machines to be used [Currie, 1996]. The dry cycle time can be estimated based on the following categories of the weight of the product for a machine that would typically be used for this component.

Product weight	Dry cycle time
0 – 60 g	0.50 s
61-200 g	0.75 s
201- 300 g	1.25 s
301 – 500 g	2.30 s
501 – 1000 g	3.30 s

7.2.6.2 Injection time

Injection time is also related to the product weight and can also be extracted from injection moulding machine plastisising rate data. It has been found that it is better to bond this information into the following categories of the product weight [Currie, 1996]:

Product weight	Injection time
0 – 60 g	1.0 s
61 – 200 g	2.0 s
201 – 500 g	2.5 s
501 – 1000 g	5.0 s

For the proposed cost estimation system, all of the above weight ranges, dry cycle times and injection times, have been built into IMCEP to enable these times to be identified automatically.

As the sub-part's weight is 5.3602 g, the dry time and injection time will be:

$$\text{Dry time} = 0.5 \text{ s}$$

$$\text{Injection time} = 1.0 \text{ s}$$

7.2.6.3 Cooling time

The Linder equation was chosen for the calculation of the cooling time because of its simplicity (see 6.6.2.2).

$$\text{Cooling Time (s)} = \frac{t^2}{2\pi X} * \ln \left(\frac{\pi * (T_m - T_w)}{4 * (T_e - T_w)} \right)$$

Where: T_m = Melt Temperature (° C)

T_w = Mould Temperature (° C)

T_e = Demould Temperature (° C)

X = Thermal Diffusivity (mm²/s)

t = Maximum wall Thickness (mm)

All of the material properties required for this calculation are held in the material data base and given the maximum wall thickness which is derived automatically. IMCEP also calculates the cooling time automatically.

$$\text{Cooling time (s)} = (2^2 / (2 * 0.128 * \pi)) \ln (\pi/4(238-45)/(94-45))$$

$$\text{Cooling time} = 5.62 \text{ s}$$

7.2.6.4 Complexity Additions

In addition to the geometric features of the product, tight tolerances, a gloss finish, the presence of undercuts, internal threads and/or cross-holes as described in chapter 6, are main factors for increasing the moulding time or complexity of the injection moulding products. For example, for a tolerance of less than 0.05 mm, a low demoulding temperature should be used. Two demould temperatures therefore, need to be contained within the material database, the upper demould temperature and the lower demould temperature. If a tolerance of less than 0.05 mm is specified then the lower demould temperature should be used for calculating the cycle time, otherwise the upper demould temperature should be used. For this research all complexity additions are entered manually and compensated for selected automatically.

To achieve a gloss finish surface a higher melt temperature of 15 °C typically needs to be used [Belofsky, 1995]. Undercuts, internal threads and cross-holes usually increase the mould opening time as extra pins, etc have to be extracted and therefore these have an effect on the dry cycle time. The effects of these factors on the cost estimation process are discussed by Currie [Currie, 1996] and how they can be compensated for simply is shown below.

- (a) If either a cross hole or an undercut is present, the cycle time is increased by 3 seconds.
- (b) If an internal thread is present, the cycle time is increased by 4 seconds.
- (c) The total increase in the dry cycle time has been limited to 4 seconds as the pin or female screw extraction happens concurrently within the mould.

For the first sub-part (rectangular plate) the complexity additions are calculated as follows.

Tolerance less than 0.05 = No

Gloss finish = No

Undercuts = No

Internal threads = No

Cross hole = No

Therefore for the 1st sub-part:

Complexity additions = 0

Demould temperature = 94

The various time elements need to be aggregated to determine the cycle time. Thus:

Dry cycle time = 0.5 s

Injection time = 1.0 s

Cooling time = 5.62 s

Complexity Additions= 0.0s

Cycle time = Dry cycle time + Injection time + Cooling time + Complexity Additions

Cycle time (s)= 0.5 + 1.0 + 5.62 + 0

Cycle time = 7.12s

7.2.7 Number of impressions in the mould

There are many empirical equations for the calculation of the number of impressions, but the most popular and simple one is recommended by Dym [1979] namely:

Number of Impressions = (Production Volume * cycle time /1000)

Therefore for the first sub-part;

Number of Impressions = (20000 * 7.11670 / 3600000) = 0.039 \cong 1

7.2.8 Cost estimation

As all the necessary information, is now available the sub-part cost can be estimated using the equations presented in chapter 3. For the first sub-part the equations become:

$$\text{EstCost4 (0-30g)} = \text{EstCost3}$$

$$\text{EstCost3 (0-60g)} = \text{EstCost2} * 0.83410 + C/N * 0.002061366 - 0.01335$$

$$\text{EstCost2 (>9000)} = \text{EstCost1}$$

$$\text{EstCost1 (0-10g)} = (W * P (1 + S)) + (-0.00172W + 0.04217)$$

Where W = Component Weight (g)

P = Material Price (£/g)

S = Scrap Rate (%)

V = Production volume

C = cycle time (s)

N = number of impression

Therefore;

$$\text{Estimated cost} = \text{Estcost4} = \text{£ } 0.077725$$

The information for the first sub-part is displayed on screen in a separate window next to the Ideas solid model (figure 7.4) and is summarised in table 7.1.

The estimated cost is includes six decimal places because, the effect of small incremental changes on the product volume and wall thickness can be seen on the estimated cost during the construction of the product.

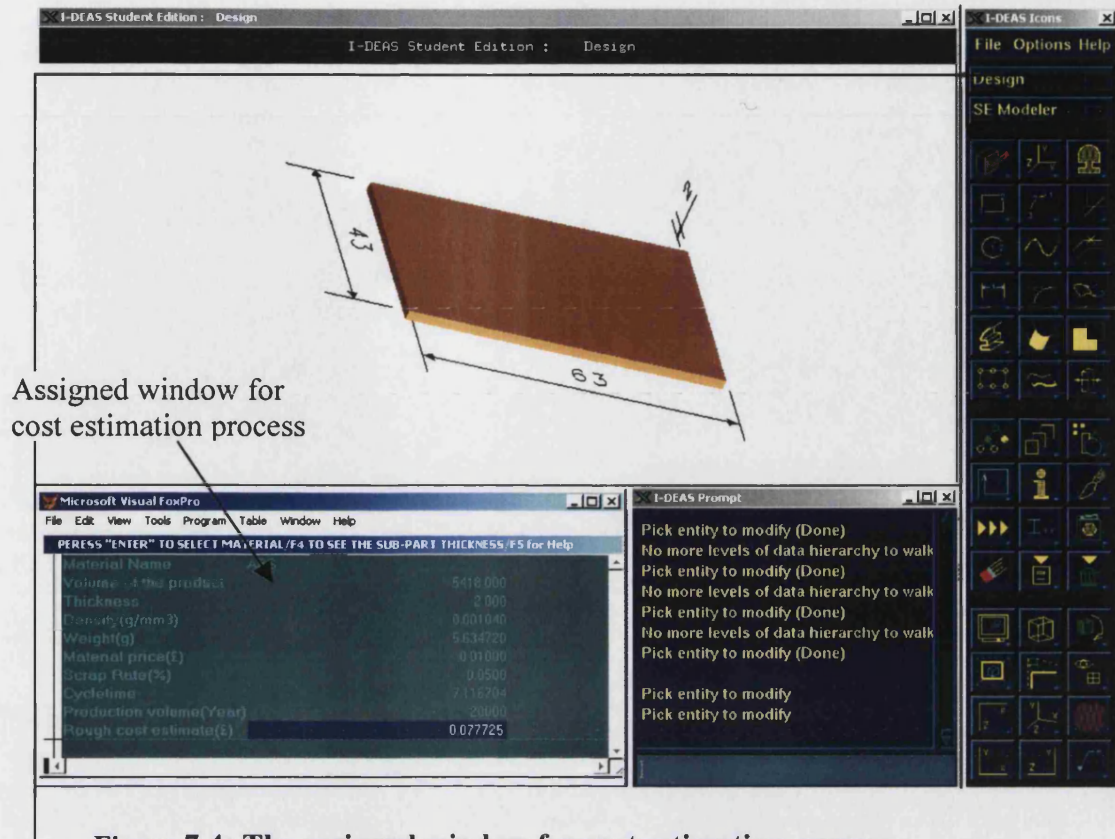


Figure 7.4: The assigned window for cost estimation process

Step	Sub-part	Volume	Material	Weight	Max Wall thickness	Cycle	Sub part
	(Flat plate)	(mm)	name	(g)	(mm)	time (s)	Cost (£)
1	1	5418.00	ABS	5.635	2	7.1167	0.077725

Table 7.1: The information for the first step of the product cost estimation process

The process of product model development is then continued using sub-part 1 and deducting the 6 flat cylinders (sub-part 2 to 5) from it (figure 7.5).

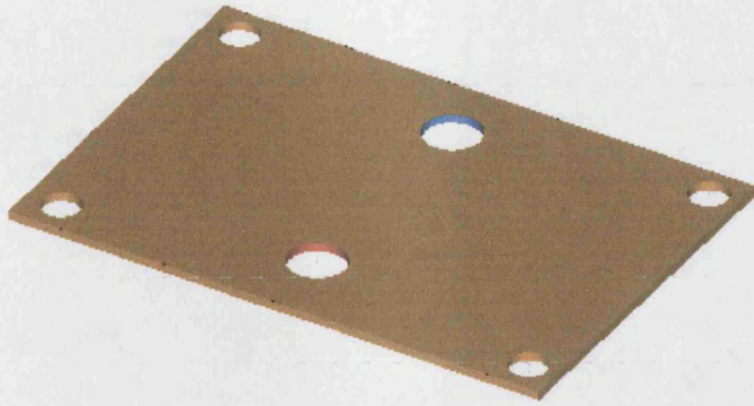


Figure 7.5: The first sub-part after deducting 6 flat cylinders

The information for this shape is summarised in table 7.2.

Step	Sub-part (Flat plate)	Volume (mm)	Material name	Weight (g)	Max Wall thickness (mm)	Cycle time (s)	Sub part Cost (£)
2	1	5204.35	ABS	5.4123	2	7.1167	0.076114

Table 7.2: The information for the first step after deducting 6 flat cylinders

Each of the sub-parts numbered 8 to 27 can be a candidate for product model development. Sub-part 8 (figure 7.6) was chosen as next part to join with sub-part 1 and the process of cost estimation was repeated. The information summarised in table 7.3 was found for sub part 8.



Figure 7.6: Next sub-part of the injection moulded product (Hollow cylinder)

Step	Sub-part (Hollow cylinder)	Volume (mm)	Material name	Weight (g)	Maximum wall thickness (mm)	Cycle time (s)	Sub part Cost (£)
3	8	77.754	ABS	0.0809	1	2.9042	0.028396

Table 7.3: The information of the next sub-part of the product

To develop the product, sub-parts 1 and 8 need to be joined (figure 7.7). This will effect the product volume, weight, maximum wall thickness (see chapter 6 section 6.2.2.2 and also figure 7.8) and cycle time. Also it could affect the complexity of the product and this needs to be considered. This joining is considered as a further aspect of complexity which can affect the cycle time calculation. These effects are again calculated automatically.

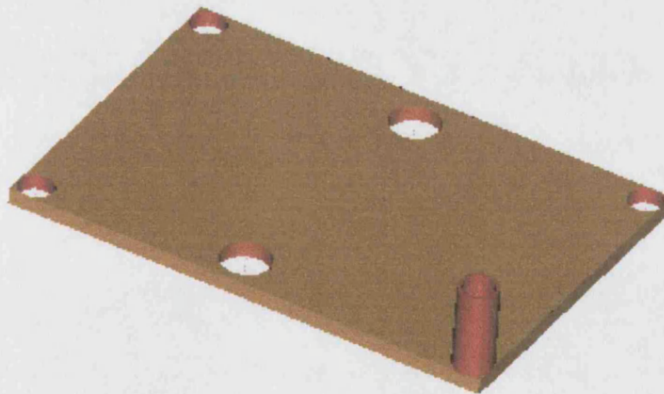


Figure 7.7: The joining of sub-part 1 and sub-part 8

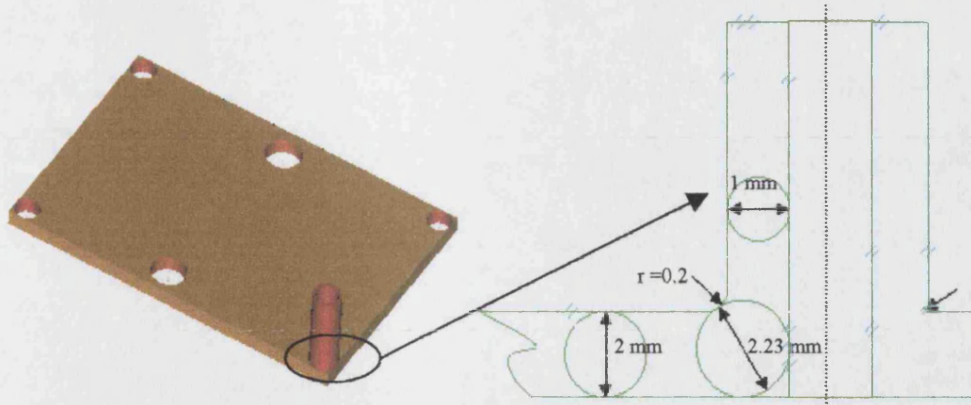


Figure 7.8: The effect of joining sub-part 1 and 8 on the maximum wall thickness

The maximum thickness of the joined section is calculated using equation 6.10 as below.

$$R = \left(\frac{(r_1 + r_2 + 2R_1)^2 + 4R_2(r_1 + r_2 + 2R_2 + 2\sqrt{(r_1 + R_2)(r_2 + R_2)})}{4(r_1 + r_2 + 2R_2 + 2\sqrt{(r_1 + R_2)(r_2 + R_2)})} \right)$$

Maximum wall thickness = 2R (mm)

It is assumed that;

From figure 7.8:

$$R_1 = 1 \text{ mm}$$

$$R_2 = 0.5$$

The filter radius; $r_1 = r_2 = 0.2 \text{ mm}$

$$R = \frac{((0.2 + 0.2 + 2 * 0.5)^2 + 4 * 1 * (0.2 + 0.2 + 2 * 1 + 2 * ((0.2 + 0.5) * (0.2 + 1))))^{1/2}}{4 * (0.2 + 0.2 + 2 * 1 + 2 * ((0.2 + 0.5) * (0.2 + 1)))}$$

$$R = 1.116 \text{ mm}$$

Maximum Wall thickness = 2 R = 2.23 mm

The results of the joining process are shown in table 7.4

Joint Step	Sub-part	Volume (mm)	Material name	Weight (g)	Maximum wall thickness (mm)	Cycle time s	Sub part Cost (£)
1	8	5282.107	ABS	5.4934	2.233	7.8407	0.079541

Table 7.4: The information of joining sub-part 1 and 7 together

Sub-part 9, the second hollow cylinder, was chosen as the next candidate to be added for the product development. The general rule is to select the sub-part with the greatest volume. The effect of this sub-part on the product information is shown in table 7.5. In summary it adds volume but no more complexity and does not affect the cycle time, as the increase in thickness caused by joining sub-part 1 and 8 is exactly the same as joining sub-part 1 and 9.

Joint Step	Sub-part	Volume (mm)	Material name	Weight (g)	Maximum Wall thickness (mm)	Cycle time (s)	Sub part Cost (£)
2	9	5359.858	ABS	5.5743	2.2315	7.8407	0.080127

Table 7.5 General information of joining sub-part 9 with sub-parts 1 and 8

To develop the product features, other sub-parts are then selected and added. The effect of each sub-part on the product weight, wall thickness, cycle time and product cost are shown in table 7.6.

Joint Step	Sub-part	Volume (mm)	Material name	Weight (g)	Maximum Wall thickness (mm)	Cycle time (s)	Sub part Cost (£)
3	10	5437.605	ABS	5.6551	2.2315	7.8407	0.080786
4	11	5515.372	ABS	5.7359	2.2315	7.8407	0.081372
5	12	5632.341	ABS	5.8576	2.2315	7.8407	0.082251
6	13	5722.478	ABS	5.9514	2.281	8.8058	0.083550
7	14	5812.478	ABS	6.0449	2.281	8.8058	0.084209
8	15	5847.478	ABS	6.0814	2.281	8.8058	0.084502
9	16	5882.478	ABS	6.1178	2.281	8.8058	0.084795
10	17	5909.967	ABS	6.1467	2.500	10.2761	0.088046
11	18	5937.456	ABS	6.1750	2.500	10.2761	0.088192
12	19	5958.662	ABS	6.1970	2.500	10.2761	0.088412
13	20	5969.162	ABS	6.2079	4.000	23.9668	0.116707
14	21	5979.662	ABS	6.2188	4.000	23.9668	0.116780
15	22	6020.162	ABS	6.2610	4.000	23.9668	0.117073
16	23	6038.912	ABS	6.2805	4.000	23.9668	0.117219
17	24	6057.662	ABS	6.3000	4.000	23.9668	0.117366
18	25	6072.662	ABS	6.3156	4.000	23.9668	0.117512
19	26	6121.662	ABS	6.3665	4.000	23.9668	0.117878
20	27	6170.662	ABS	6.4175	4.000	23.9668	0.118245

Table 7.6:Information of the product model development and the estimated cost

The cost information is made available in two different ways namely ‘edit’ (figure 7.9) and ‘browse’ (figure 7.10) to the designer on screen as the product model is developed.

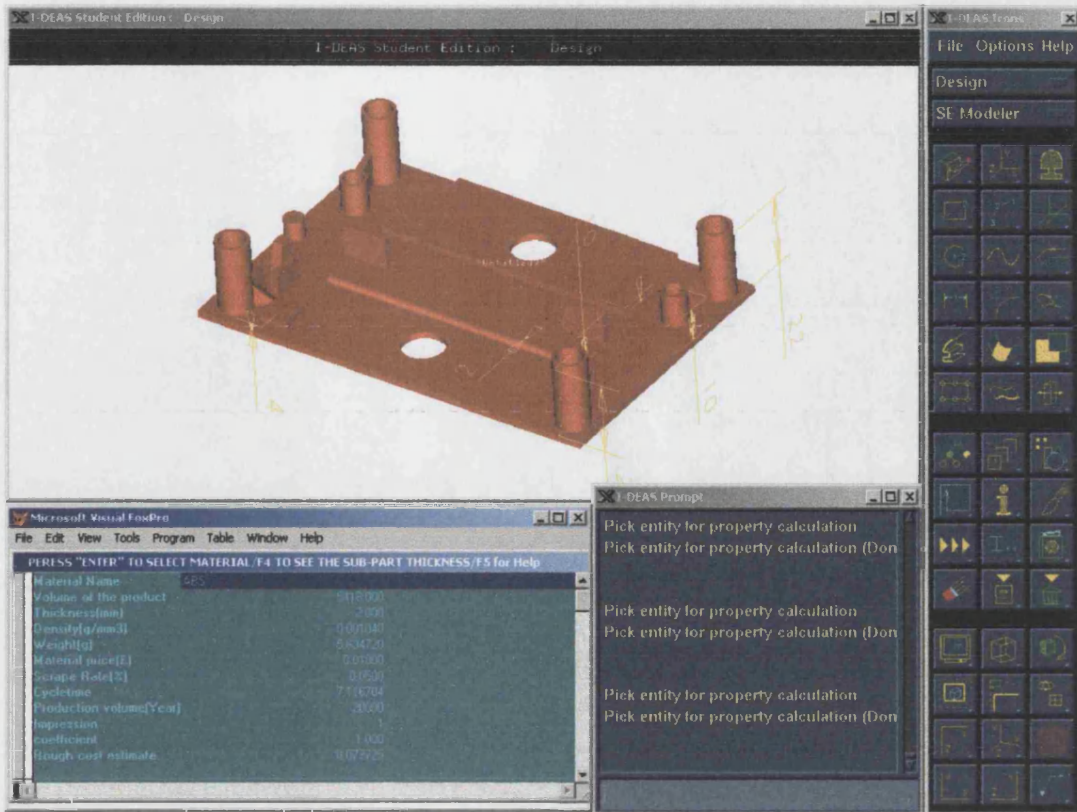


Figure 7.9: The Edit method of depicting the information

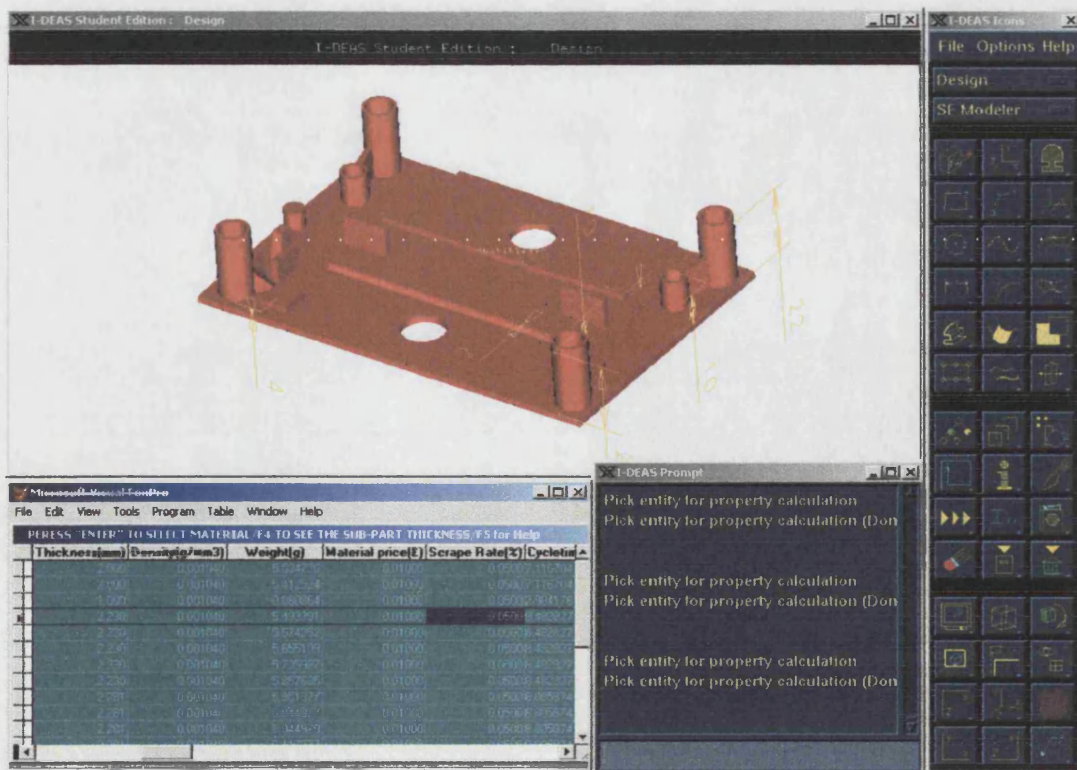


Figure 7.10: The browse method for depicting the information

This information can be also displayed graphically on screen after saving in files (figure 7.11). The main benefit of the graph is that it helps designers to see, which sub-parts have a significant affect on the product cost. They would be able, to analysis the sub-parts for necessary changes. This can help the designer to design to minimise product cost.

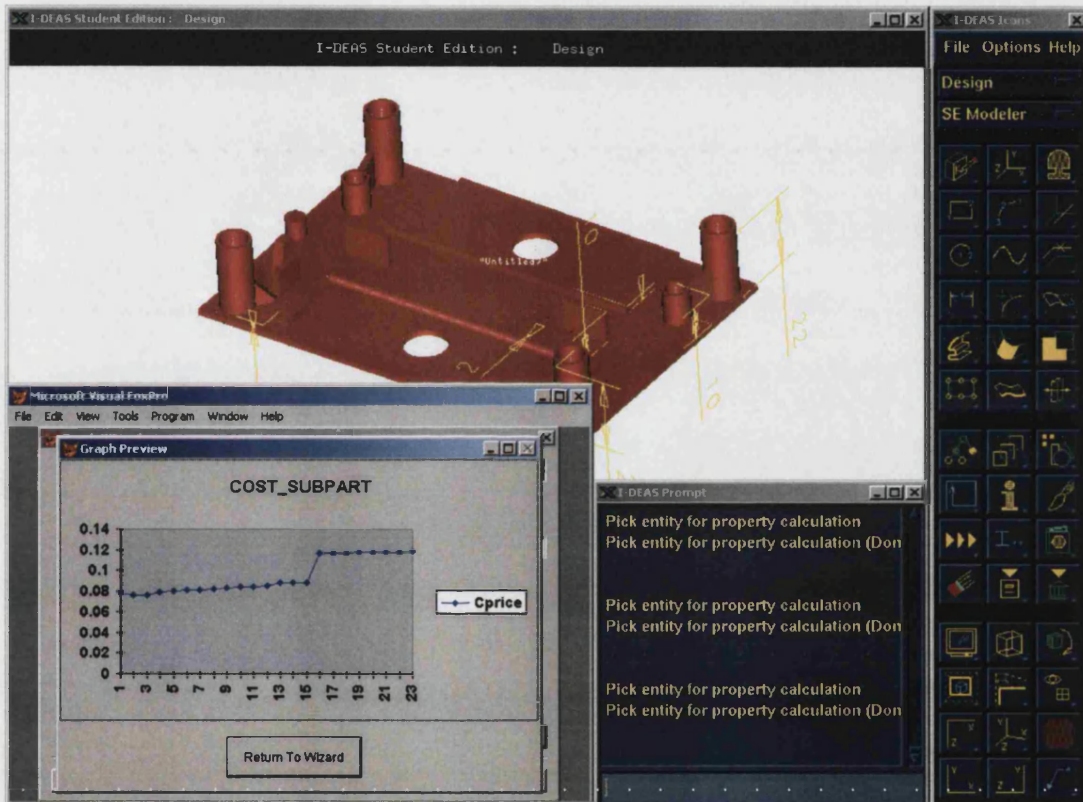


Figure 7.11: The graph of estimated cumulative product cost against the product sub-part

7.3 Discussion

For this example, as the graph in figure 7.11 shows, the sub-part numbered 20 (figure 7.12) increases the product cost from £0.088412 to £0.116707. This change is considered to be a large change in the product cost.

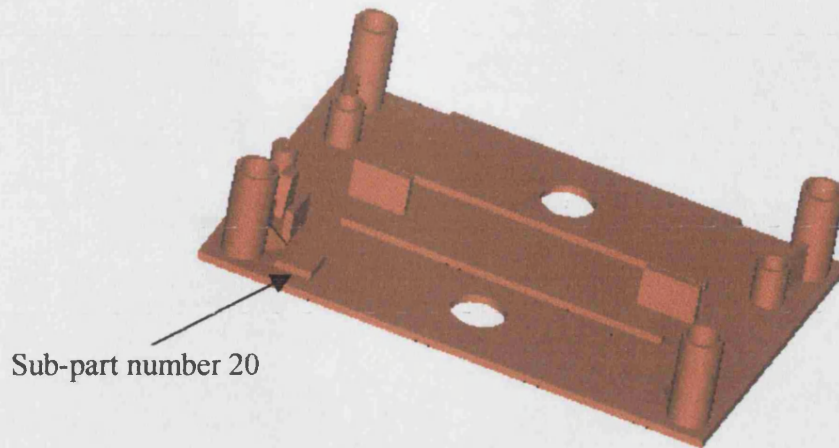


Figure 7.12: Sub-part number 20 of the injection moulded product

As the change in the product weight from 6.20g to 6.21g is not considerable, and no complexity additions are applied, the only reason for this large cost increase is an increase of the product wall thickness. Based on the information obtained during the product cost estimation, which is shown in table 7.5, it is at this step of the product model development that the product wall thickness has increased from 2.5 mm to 4 mm. This increase has changed the product cycle time from 14.2761s to 27.9668s and as a result the product cost has changed from £0.088412 to £0.116707. This information could assist the designer to investigate any possibilities for changing the sub-parts thickness. For example, if the maximum thickness could decrease from 4 mm to 3 mm, then the estimated cost would decrease to £0.096515. If this happened, the new cost would be displayed for consideration by the designer and is shown graphically in figure 7.13.

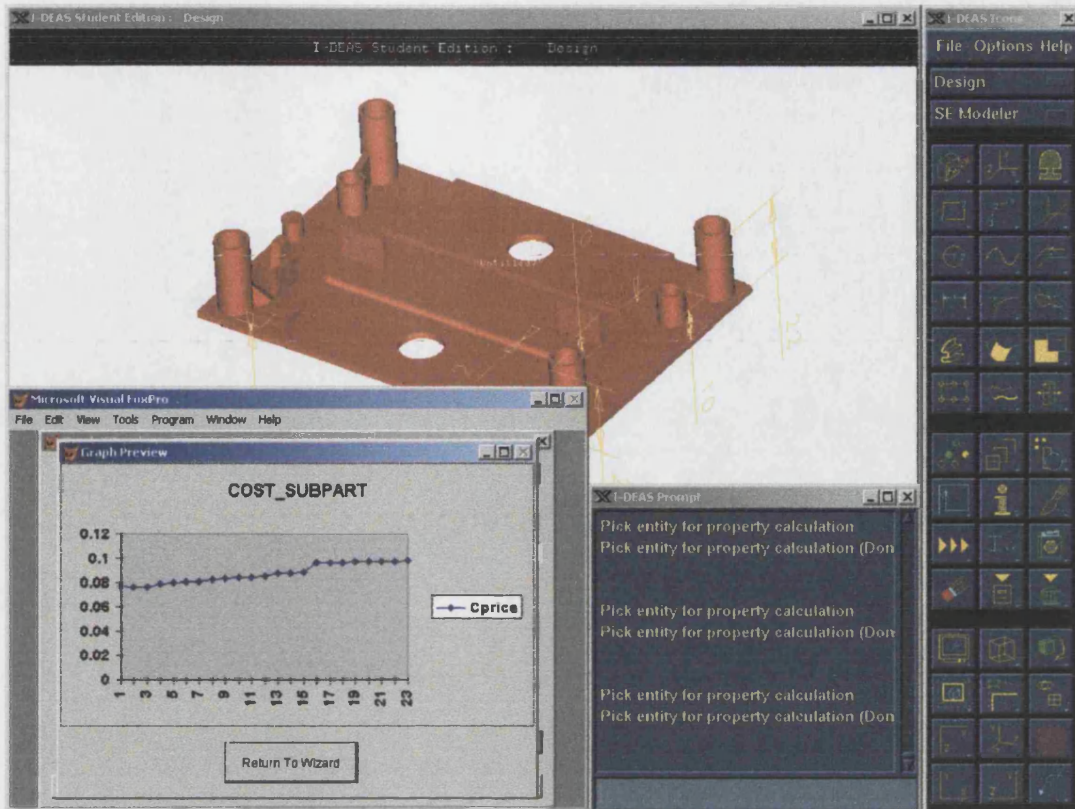


Figure 7.13: The graph of the estimated product cost against the product subpart after reducing the wall thickness for sub-part 20

Chapter 8

Results and discussions

8.1 Introduction

This chapter describes the elements of the proposed cost estimating system and critically discusses its methodology and the results it has achieved. Although, the research set out to establish a system of cost estimation that was generic, fast and reliable, it was decided to develop the system for injection moulding components only to illustrate its approach. The costing logic used is specific to injection moulding and although the methodology is considered it could be largely generic, has not been tested on other processes. This chapter also discusses the advantages and disadvantages of the methodology used.

8.2 The main factors for the proposed cost estimating process

The relationship between the main factors of the proposed cost estimating system are shown in figure 8.1. Some of these factors are critically discussed below.

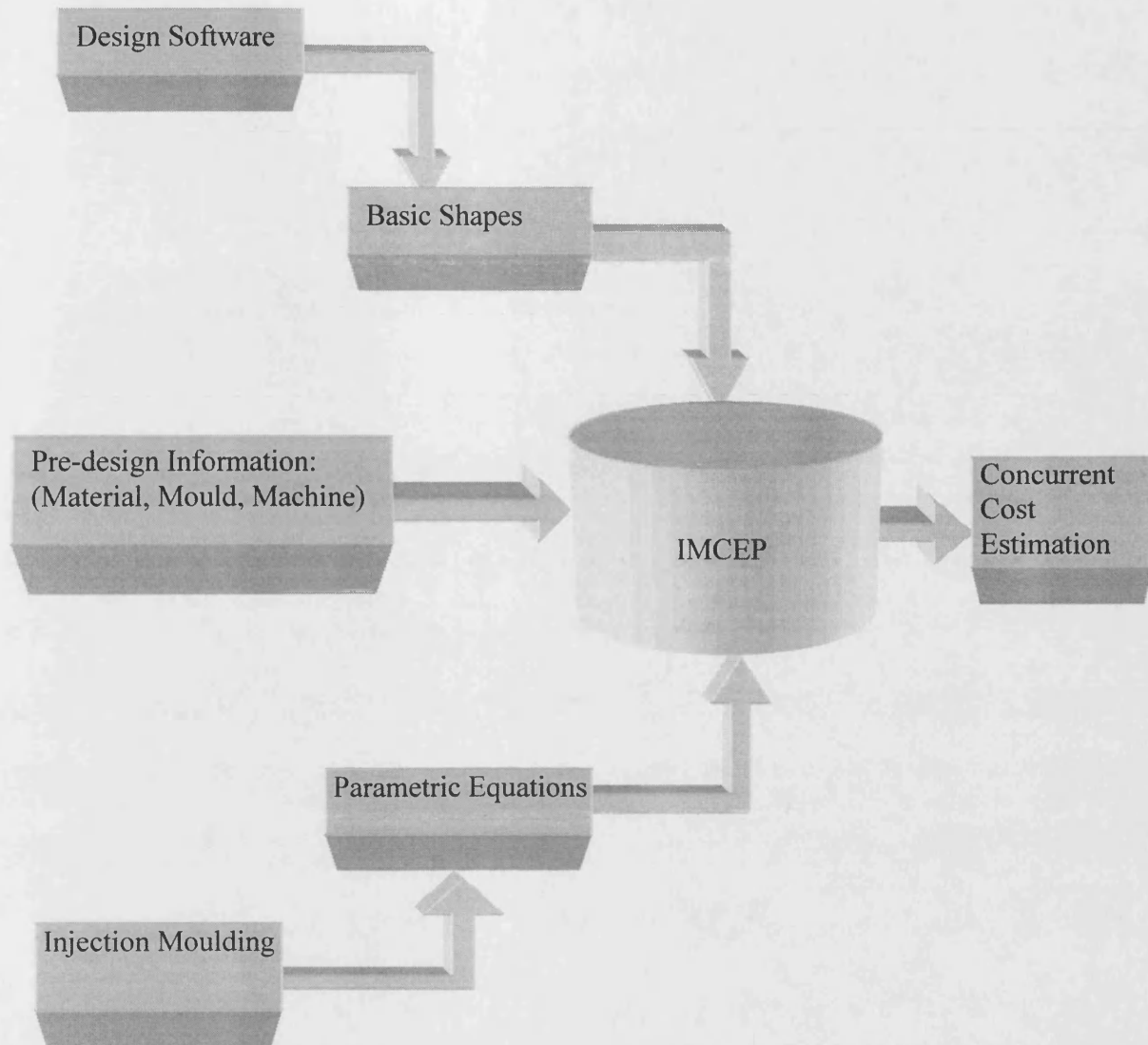


Figure 8.1: The relationship between the main factors for the proposed cost estimating process

8.2.1 Design Software

There are a number of software products that can be adopted for the design process, each of them have their advantages and disadvantages. For this research work, the Ideas software package was considered to be a powerful design tool and has been used for product design. Although, using this software has many advantages,

some of its restrictions make the use of this software, for cost estimation difficult. For instance, the extraction of the dimensions of the designed shape could not be achieved easily. To extract the dimensions, a large amount of data needed to be filtered and classified. This is because design software in general, has been developed to meet a specific need or is aimed at a specific area of design. Changing the format of a package's output information or providing specific new output information is not easily managed and this is the case when using Ideas.

To calculate the product cost, at the early stage of design, the product's volume, its dimensions and the information about the joined sections are assumed to be the necessary primary information, but it was found that this information could not be transferred automatically and concurrently from Ideas into the IMCEP files to achieve a fully automated cost estimation process. This information needed to be sent using various designer activated icons. For example, the dimensions are transferred using the information icon, the volume of the product is transferred using the properties icon and the information of the joined sections is transferred by adding them into the dimensions information.

To solve the problem of data transfer for the proposed cost estimation system, a "Help" program has been provided using the FoxPro software, that can be used during the design process to facilitate concurrent cost estimation. This program is accessible when the FoxPro cost estimation program is activated and can be run by pressing the "F5" button on the keyboard. Although, this program is considered to be helpful to the designer during the process of cost estimation, there is still a need to use the specified design software's icons for forwarding concurrently the information necessary for the cost estimation process.

8.2.2 Basic shapes

As discussed, in chapter 5, it is proposed that the process of injection moulding product development can be performed using a set of 17 basic shapes which have been identified from an analysis of 50 injection moulded products. However, as discussed in chapter 5, the diversity of the shapes that can be produced by the injection moulding process is infinite and it is anticipated that there will be shapes that are difficult or even impossible to design, using the designed basic shapes. Although, this is a limitation of the proposed system the basic shapes have been designed as flexible as possible to maximise the size of the current product domains. In addition, there is the possibility of adding new shapes to the developed set of basic shapes to cover a larger set of injection moulding products. However for this research it was considered that the basic shapes used would enable a research system to be developed that would test the validity of the methodology. It should be noted that, although curved surfaces were built into a number of the basic shapes developed, it was found from the products analysed that a large percentage of all products could be covered without having a free form curved basic shape. This type of basic shape could be added by further research.

During product model development, it would also be useful if the effect of each sub-part on the cost of the necessary mould, and machine, were also identified accurately and added to the IMCEP program.

8.2.3 Material database

As described in chapter 6, the material database contains a selection of injection moulding materials. This database should be extended to include a wider range of injection moulding materials being stored. The database has been designed to allow

for expansion and to facilitate this a FoxPro program has been written that enables the designer to add, delete and edit material information.

8.3 Advantages of the proposed cost estimation methodology

Some advantages of the proposed cost estimation process are summarised below.

8.3.1 Cost estimation with minimum knowledge of manufacturing process

The main aim of this research was to provide a methodology for developing a concurrent early cost estimating system that is usable by designers who are unfamiliar with the specified manufacturing process. It is considered that this objective has been largely fulfilled as the main factors of estimating the cost of injection moulded products such as product wall thickness material properties and volume are calculated and used by parametric equations automatically. Therefore, there is no need for the designer to be involved with the necessary steps of cost estimation other than transferring information using a set of icons.

8.3.2 Easy cost estimates and cost documentation

The proposed methodology is easy to use, provides fast cost estimates and cost documentation. The steps of the cost estimation process are shown on the screen concurrently with design activities (figure 8.2). Also, the cost estimation “Help”

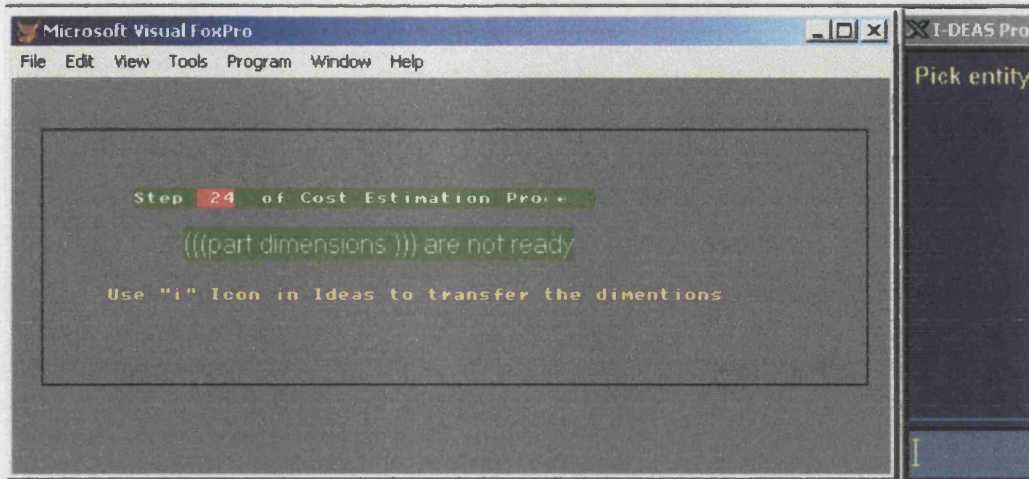


Figure 8.2: On screen steps of cost estimating process

(figure 8.3) facility provides an environment that eliminates any possible ambiguity of the cost estimation methodology. Cost information is documented concurrently with the cost estimation process and the information is saved into files that are accessible during and after the cost estimation process. The cost documentation enables the designer to analyse each stage of the product development and its related cost. Also, the relationship between the product cost and the product sub-parts can be displayed graphically to provide a more visible result for the designer.

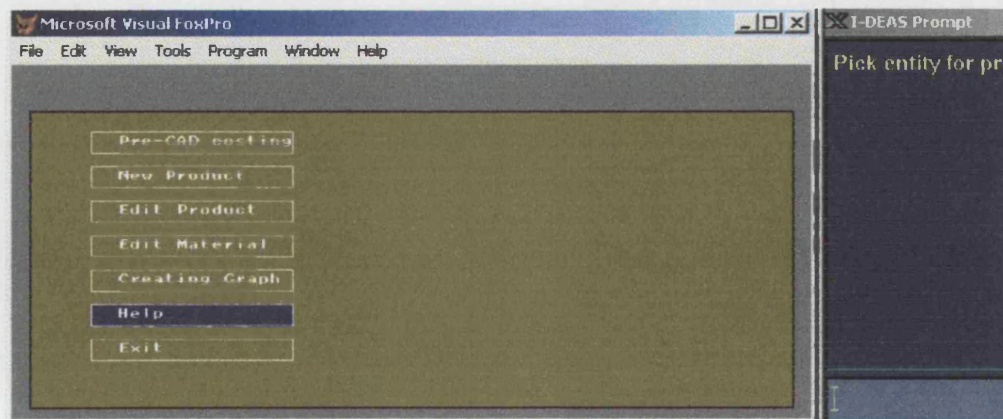


Figure 8.3: Help program for IMCEP

8.3.3 Using the advantages of three cost estimation methods

Three methods of cost estimating, which are; feature based costing, expert system, and parametric system are used together for the proposed cost estimating methodology. This reduces the limitations of using each method individually, as described in chapter 2. Also, the proposed methodology gains the benefits of the three methods used.

8.3.4 Advisory method of product development

During the product development, the effect of each sub-part on the product cost is shown concurrently. This enables the designer to see the changes to the product cost when a feature is added or edited. Having this ability, the designer is able to design to minimise the product cost within the functionality required. Hence, the proposed system not only provides concurrent cost estimation, it also provides an advisory system for the designer to design products with the lowest possible cost by highlighting the contribution of the product's sub-parts. This provides the possibility of analysing and changing the design of the sub-parts.

8.3.5 Facilitate the design activities

As described, a set of generic basic shapes have been developed for injection moulded products. Using generic features decreases the design process activities. For example when designing a three-dimensional complex plate the only necessary activity is editing the basic shapes dimensions instead of creating a new rectangular shape with a curved edge, from first principles. Therefore, the proposed methodology

should make the design process more productive as well as providing a concurrent cost estimate.

Chapter 9

Conclusion and achievement

The main aim of this research was; to develop a concurrent cost estimating methodology suitable for use at the conceptual stage of the design process that enables the designer to analyse the product cost. It is considered that this aim has been fulfilled and;

- A concurrent method of cost estimation at the concept stage of design has been developed.
- The time and effort for cost estimating have been reduced.
- Improved design phase cost documentation has been provided.
- The visibility of cost and feature relationships has been increased.
- The designer productivity has been improved by eliminating the manual searching of cost data files.
- The cost estimation reliability has been increased by eliminating manual errors.
- The cost estimation performance for designs has been improved.
- An automated cost estimation system has been developed.
- An on screen method of cost estimation has been created.
- A set of potentially generic basic shapes for product construction has been developed.
- A method of material selection during the product development has been achieved.

Chapter 10

Recommendation for further work

It is the author's experience that the proposed system works, and the product cost can be estimated concurrently although additional capabilities would be advantages. Work could be undertaken in order to fully automate the injection moulded cost estimation process (IMCEP). Several areas of the documented research could be investigated further. These include;

- The most important area requiring further investigation is the relationship between component features, mould and machine. As the product model develops and features are added the mould shape and mould parts could change. It could affect the mould and machine specification and needs to be investigated accurately and added to the IMCEP.
- Using the IMCEP under a wider range of basic shapes would be useful in determining its capability. Further work in analysing a larger number of injection moulded products to investigate the necessity of new basic shapes for injection moulded product would enhance the IMCEP.
- The costing logic used is specific to injection moulding and has not been tested on other processes. It would be of great interest and applicability to further develop this work and ascertain the basic shape requirements for other processes.

This could then ensure that the IMCEP can be applicable in other sectors and benefit the development process.

- The provision of a fully automated concurrent product cost estimator needs to be investigated.
- Work need to be performed to test the mouldability of the designed product during or after the design process.
- The effect of the tooling cost on the estimated cost needs to be investigated.

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Appendix A

Ideas software package

A.1 Introduction

This appendix is designed to help the Ideas user to design the product in a proper way in order to achieve the maximum benefit of the cost estimation. The following sections explain; (1) How the user should create a part. (2) How the user should modify the part. (3) How the user should name the part (4) How the user should join a part. (5) How the user should see the information (6) how the user should calculate the part volum.

A.2 Running Ideas

The Ideas can be run using the following steps.

Step 1. Clicking on the Ideas Icon.

Step 2. Assigning a unique project name.

Step 3. Assigning a unique file name

Once this has been completed the main screen of Ideas will be shown as depicted in figure

A.1

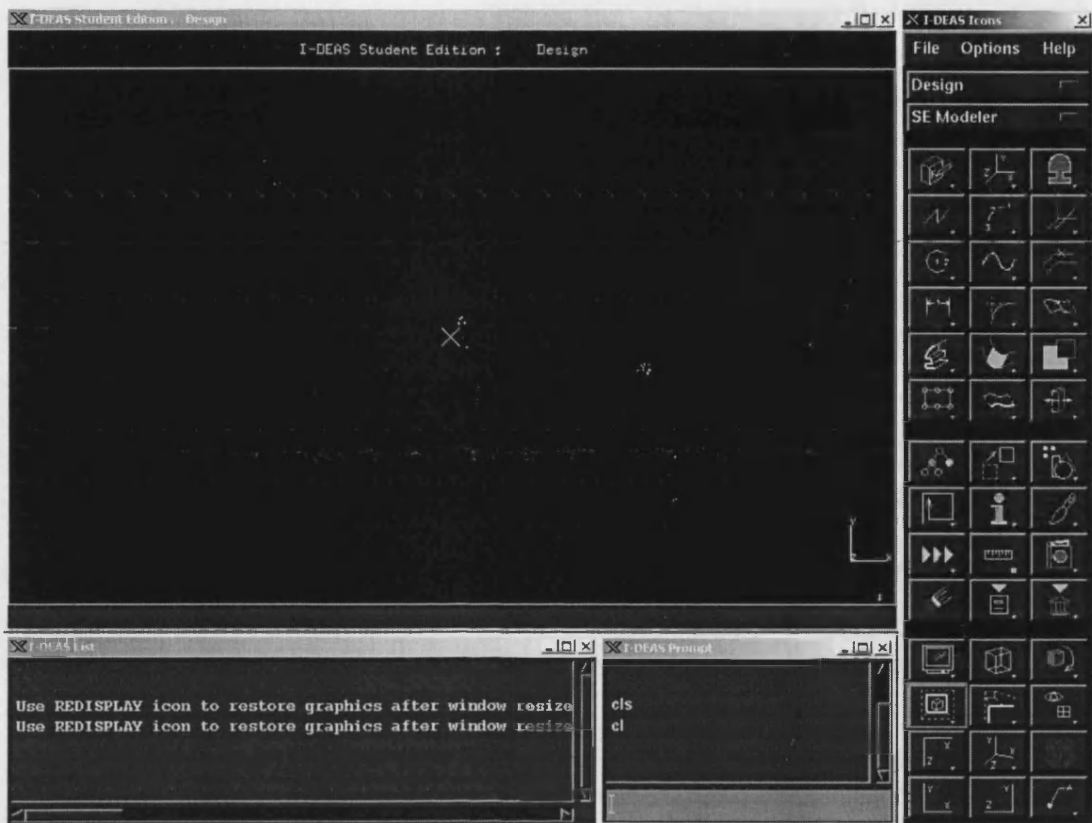


Figure A.1: The main screen of the Ideas software package

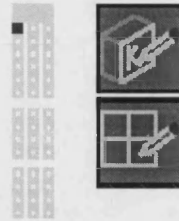
A.3 Creating a part

Creating a simple part is typically a 3-step process:

- Picking a sketch plane.
- Sketching.
- Creating a feature.

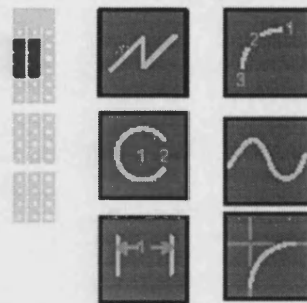
Picking a sketch plane is possible using the following icons.

Picking a sketch plane



To create a simple part, it is necessary to use the provided icons. Begin by using the Polylines icon to sketch a closed shape.

Sketching



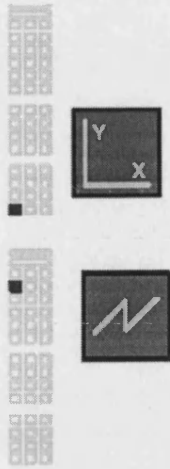
Creating features is possible using the following icons.

Creating a feature



The sketching and creating a feature are given in more detail in the following.

To sketch a closed shape as shown below the designer uses the two dimensional icon.



sketch the boundary as shown below, using the left mouse button to pick points 1 through 7



After picking point 7, terminate the command by pressing the middle mouse button.

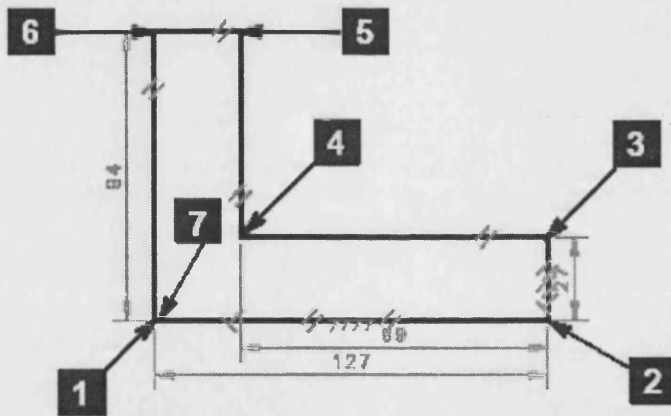
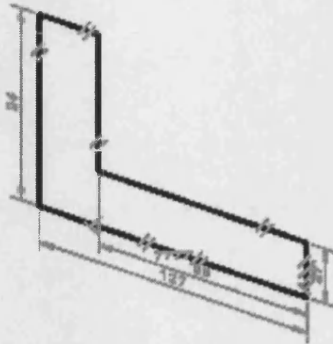


Figure A.2: A closed sketch for creating a part

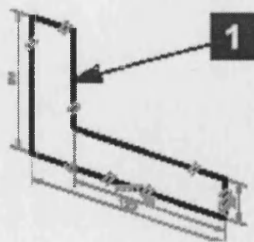
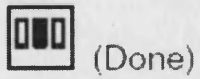
Change to isometric view.




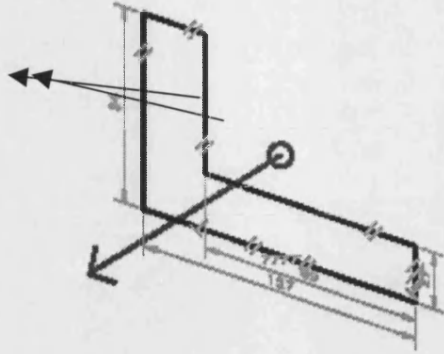
This will give a better view of the next operation. Next, extrude this shape with a desired depth using the following icons.



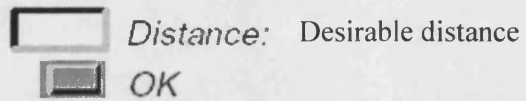
1 pick any line



 Move the Extrude Section form to get a better look at the sketch.



Extrude Section form



Using the following icon provides a wire-frame feature (figure A.2) and a solid feature (figure A.3) of the part.

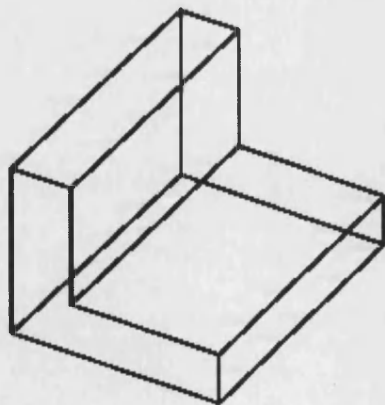
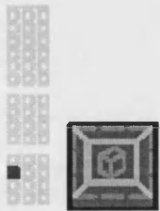


Figure A.3: A created wire-frame feature using the Ideas software

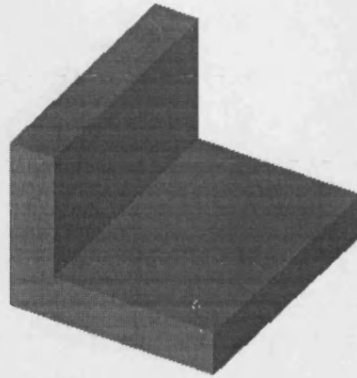
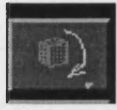
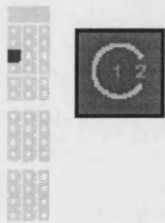
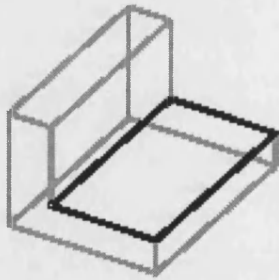
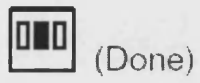
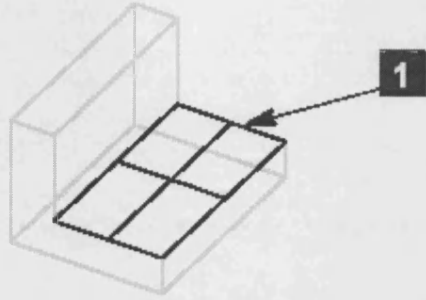
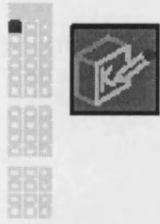


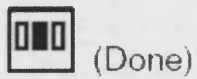
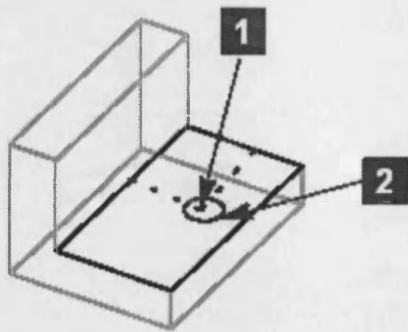
Figure A.4: Solid feature created using the Ideas software

A.4 Adding feature

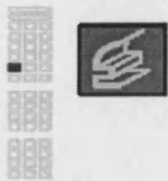
To add a feature to a part, it is necessary to follow the same process as it was for creating part. In this case, it is necessary to sketch on an existing part face. When the sketch is selected in the place icon, it will prompt the user to select to a face. The face selected will be outlined in the workplane color, and the original workplane will disappear. These are the graphical feedback clues that tell the user that they are working directly on the face of a part. In this section, they will add a cut-out feature to the part created by selecting a face and extruding a circle through the part as the following shows.



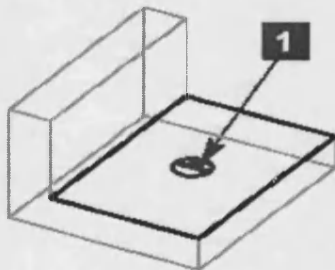
- 1 click where you want the center of the circle
- 2 click where you want the edge of the circle



Next, cut the circle through the part.

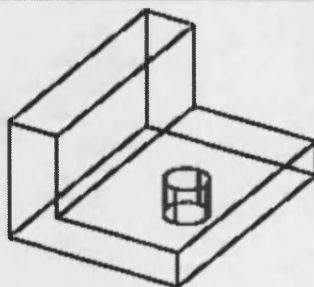


- 1 pick circle



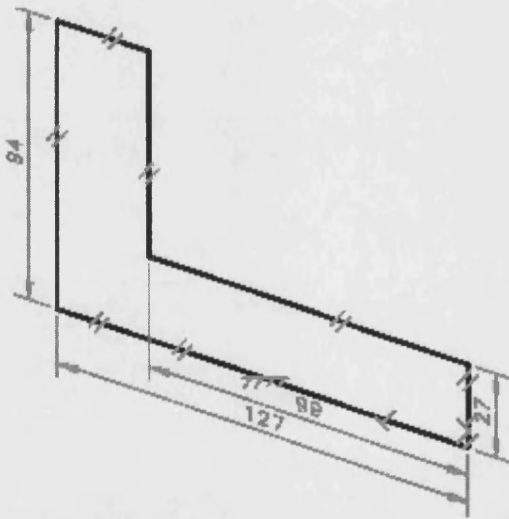
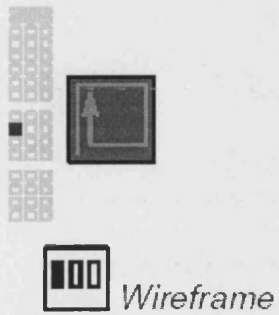
Extrude Section form

- Cutout (toggle on)*
- Depth:*
Thru All
- OK*



A.5 Modifying a Part

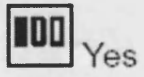
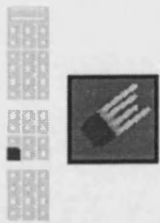
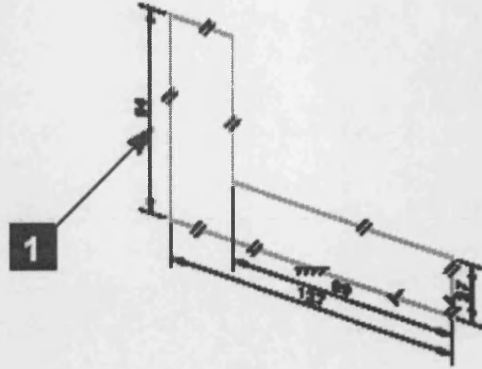
Modifying a part is possible using the modify icon. the following illustrates this.



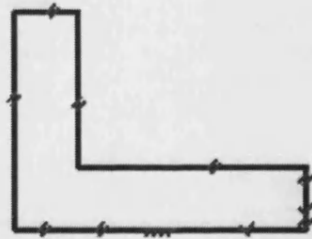
With the feature's original wireframe opened, it is possible to modify the dimensions or add new ones.

Delete all the dimensions (if there are any showing).

1 pick dimension



Switch to front view.

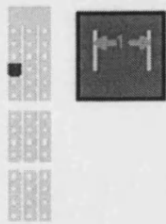


Dimensions can be created:

- line –to– line (if lines are parallel)
- line –to– point
- point –to– point

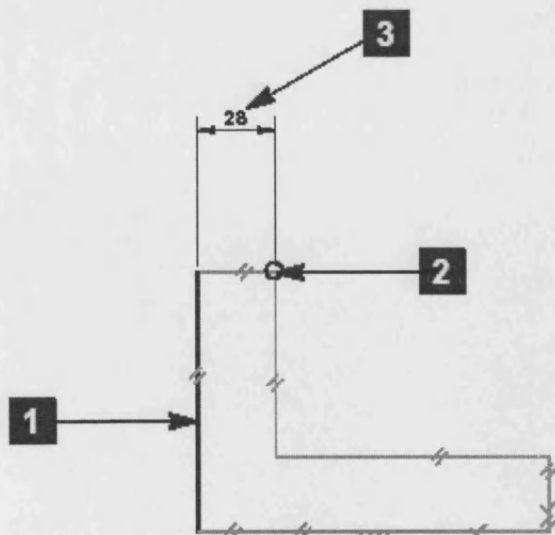
In many cases, line –to– point, which is the distance perpendicular from the line to the point, is preferred over point –to– point.

Practice creating dimensions as shown in each of the next few examples. Use line –to– point for each.



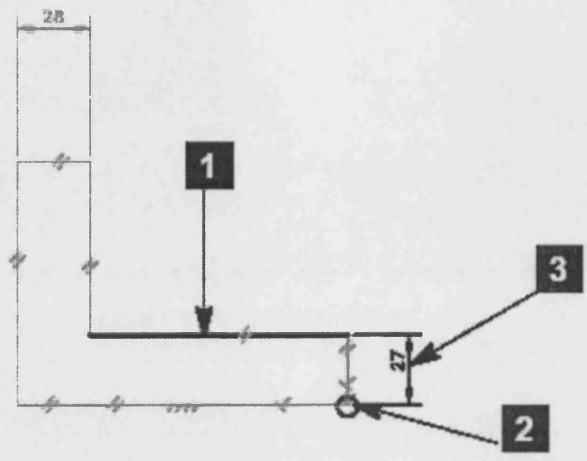
Example 1:

- 1** pick line
- 2** pick point
- 3** place the text



Example 2:

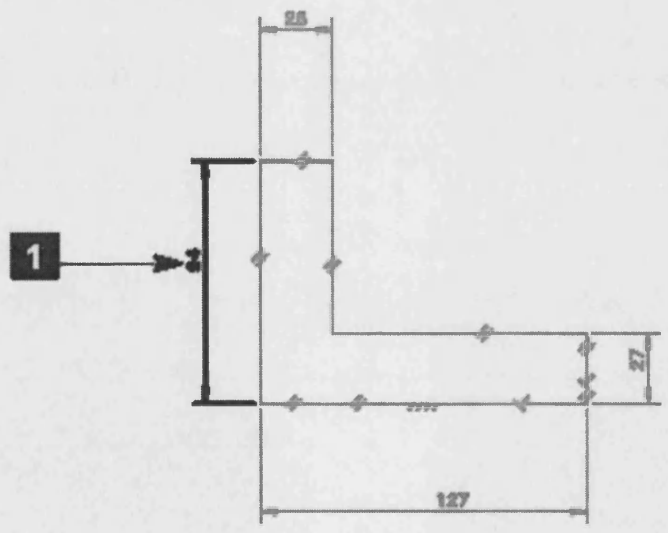
- 1** pick line
- 2** pick point
- 3** place the text



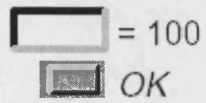
Use the *Modify* icon to modify two of these dimensions.



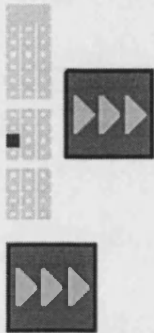
- 1** pick dimension



Modify Dimension form



To finish the part, update it twice. The first time updates the specific feature, the second time continues the update through the history tree.

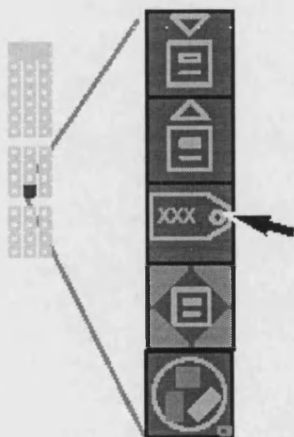


Change to isometric view.



A.6 Specifying a name to the part

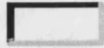
Giving a part a name is possible using the following icon.





pick anywhere on the part

Name form



Name: Corner Bracket



OK



(Done)

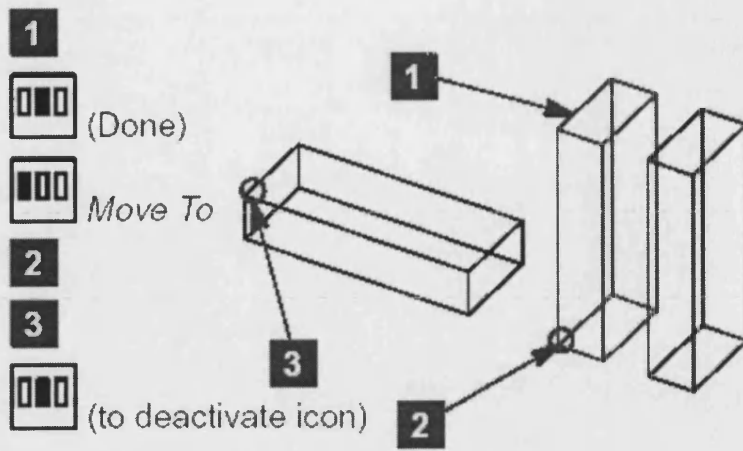
A.7 Joining parts

When parts are joined, the operation can optionally store a relationship that defines how the features are to be positioned. This relationship is stored with the part so that if modifications are made, the feature will be repositioned using the same relationship.

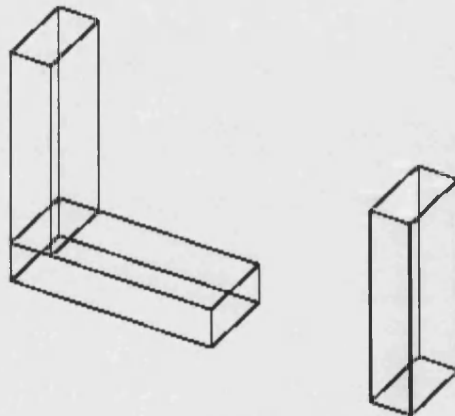
A join can be made quickly without creating a relationship, but the results may not be the same as expected when the dimensions are modified later. This section demonstrates joining features with and without associative relationships.

- Join without relationship

For a join process without relationship the following icons need to be used.



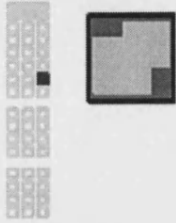
The result is shown following.



- Join with relationship

Following icons need to be used for join with relationship.

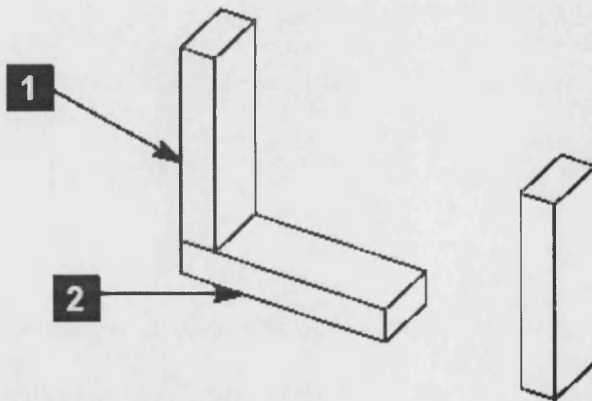
Make sure the *Relations* switch is OFF when you join the two blocks.



check the *Relations* switch in the menu

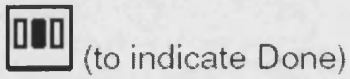
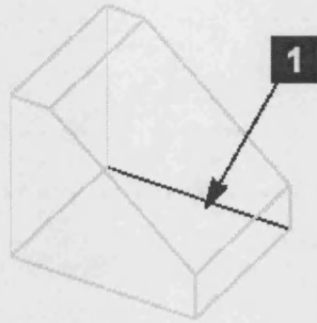
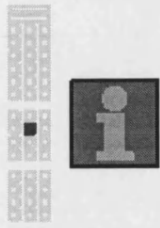


Select only if the menu says *Turn Relations OFF*.
If the menu has *Turn Relations ON*, move the mouse pointer off the menu without selecting anything.

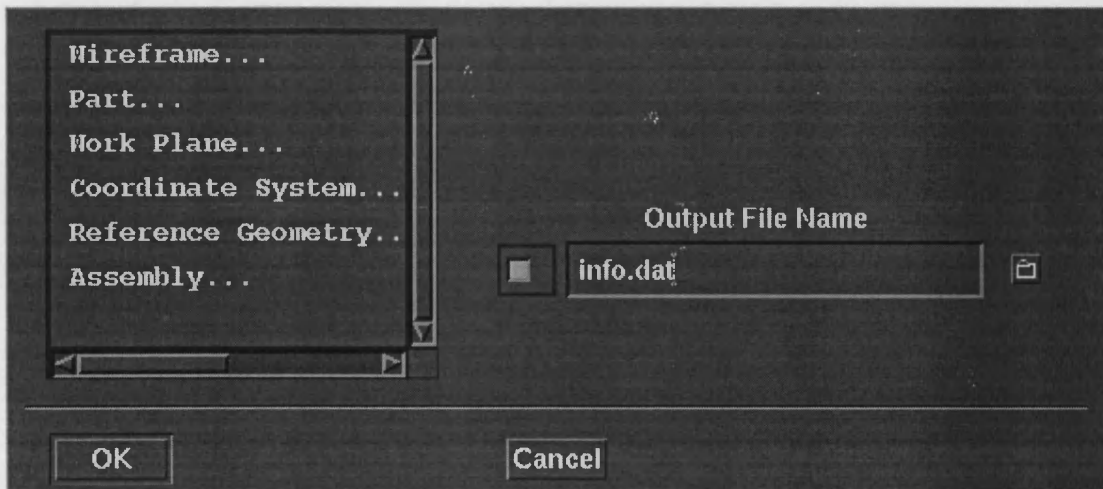


A.8 Part information

It is possible to use the “Info” and “Info options” icons to get information about any entity that can be selected, such as a line, curve, part, instance, or assembly. The “Info” icon is shown below.



The part information can be seen in the Ideas list window. For sending the information to the output files the following icon need to be used.



Output file for Ideas designed shape

A.9 Part volume

Part volume can be calculated using the icon below and using calculation from the related form.



Units : mm (milli-newton)

Part →

Material ?

Solid Surface Area Density

Open Surface Area Mass

Volume

Center of Gravity →

Properties window for the Ideas designed shape

The part volume can be shown in the form and can be sent into files by icon “i” in the above form.

Appendix B

Visual FoxPro 7.0

B.1 Introduction

Microsoft Visual FoxPro 7.0 is an application, a language, and a set of application development tools. Visual FoxPro tools are written in the Visual FoxPro language and are themselves based on tables.

In Visual FoxPro, it is possible to use wizards, builders, or commands to create or manipulate tables of data quickly. It is possible to use the Import and Table wizards to create tables, the Table designer to manage tables, and the Visual FoxPro Browse command to view tables.

Visual FoxPro provides the tools required to create and to manage high-performance, database applications and components. With its robust tools and data-centric object-oriented language, it is possible to build modern, scalable, multi-tier applications that integrate client/server computing and the Internet.

For simple access to data, use Visual FoxPro directly from commands, menus, and the Data Session window. For more complex data access and manipulation, it is possible to create forms, reports, or views to enter and display tables.

This Appendix describes how to access existing data with the Import wizard and how to create the structure for new data using the Table wizard and the Table designer from Visual FoxPro menus.

B.2 Type of Data in FoxPro

Visual FoxPro works with and manipulates data in tables. The data can be comprised of any of the following types of information, either alone or in combinations: Character, Currency, Date, Date-Time, Logical, Numeric, Float, and Double. Visual FoxPro also accesses objects (such Text files, Microsoft Word and Microsoft Excel documents), graphics, and sound files, as data.

It is possible to use data that resides in many different kinds of tables, including tab or comma-delimited text files or tables produced in other applications, such as Excel or Microsoft Standard Query Language (SQL) Server.

More information on valid data types is accessible in "Data and Field Types" in the Visual FoxPro Help.

B.3 Importing Data into Tables

To get data that is already in tabular format, it is necessary to open Visual FoxPro and import the file using the Import wizard. To create the data in Visual FoxPro, it is necessary to use the Table wizard.

- **The Import Wizard**

The Import wizard gives the option of importing text files in which data is delimited by commas, spaces, tabs, or other separators. When the Import wizard is used to copy the data into a new Visual FoxPro table, it is necessary to know how the text is delimited. In addition, it is necessary to assure the same character delimits all the fields, otherwise, the data will not import correctly.

To use the Import wizard:

1. Select the Import option from the File menu.
2. Click the Wizard button in the Import dialog box (Figure B.1).

It is possible to use this wizard for other data formats, but it is especially good for text files. For example, if a file is created in Microsoft Excel, it is possible to select Excel from the list provided in the Import wizard. If the users are familiar with another data-generating application, it might be easier to output a delimited text file from that application for importing into Visual FoxPro.

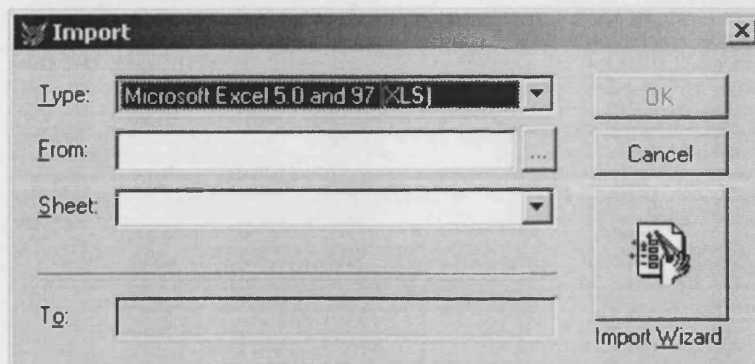


Figure B.1: Visual FoxPro Import dialog box

- **The Table Wizard**

When the Table wizard is used to create a new Visual FoxPro table, it is necessary to know the type and maximum size of the data that is planned to be placed in each field. In addition, it is necessary to consider how the data will be entered and used so the user can decide whether to allow null values.

The Table wizard provides many templates that can be used or customized:

1. Business templates: The wizard offers 26 templates for data that might use in commercial environments and transactions.
2. Personal templates: The wizard offers 20 templates for items or activities related to hobbies, household, or personal possessions.

To use the Table wizard:

1. Select **New** in the **File** menu.
2. In the **New** dialog box, click **Table**, and then click the **Wizard** button.

After the template selected, follow the remainder of the wizard steps to select fields, specify whether and how the table is indexed, and specify whether the table is a free table or contained within a database. When the wizard completed, Visual FoxPro creates the empty table structure that have been specified. Then It is possible to save the table structure and view the table, modify the new table in the Table designer, or move on to something else entirely.

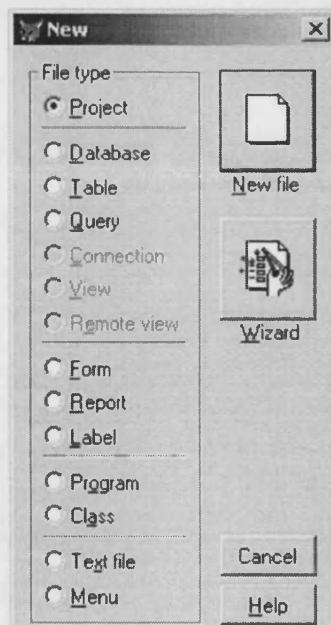


Figure B.2 Visual FoxPro Table wizard Dialog box

B.4 The Table Designer

To create a table without a wizard, the Table designer needs to be used. In the Table designer, it is possible to enter the name, data type, and size of each field. In addition to these characteristics, having opportunities to specify the decimal value width of numeric fields, whether there is an index, and whether NULL values are allowed.

If the table is in a database, specifying input and display formats, field validation rules, and value tip messages is possible

To access the Table designer:

1. Select **New** in the **File** menu.
2. In the **New** dialog box, click the **New File** button (figure B.2).

B.5 Arranging Data in Tables

Visual FoxPro tables can be free or contained in a database. A database (.dbc) file can contain one or more tables, views, connections, and stored procedures.

It is possible to access the data in a free table from anywhere, even from one or more databases.

To open a free table and its database:

1. From the **File** menu, select **Open**.
2. In the **New** dialog box, select **Table**, and then click either the **New File** button or **Wizard** button (figure B.2).

Note If the table is contained in a database, the **Open** command opens the table and the containing database.

Although the access is restricted databased tables, a database provides many properties that make this restriction worthwhile. One indication of this is when the Table designer is used to design a free table, the dialog box provides three simple tabs, but during design a databased table, each tab provides significantly more options. For simple access and viewing, free tables are quite adequate.

Tables can be simple or complex. It is possible to make using data in tables more efficient through good planning in carefully designing not only the table structure, but also the table relationships.

For example, if the designer is designing an invoice tracking system, they could create one table to hold all of the information on each invoice. It would be more efficient, however, to create tables that contained information on customers (name, address, phone numbers, customer ID, and zip code), inventory (item, cost, price, quantity on hand, and supplier), suppliers (name, address, phone numbers, ID, discount info, and contact), and other categories (zip code, city, state, and so on). Then, these tables would combine to produce invoices at one time, vendor orders another time, and reports of various kinds, including billing statements, at other times. Each individual file would be more manageable. Duplications could be eliminated and daily or repetitive operations would take less computer and personnel time. Some data entry would be simplified, enhanced, or eliminated because the related tables would get the information automatically.

More information on designing tables, are in "Choosing Data Types" in the Visual FoxPro Help (figure B.3).

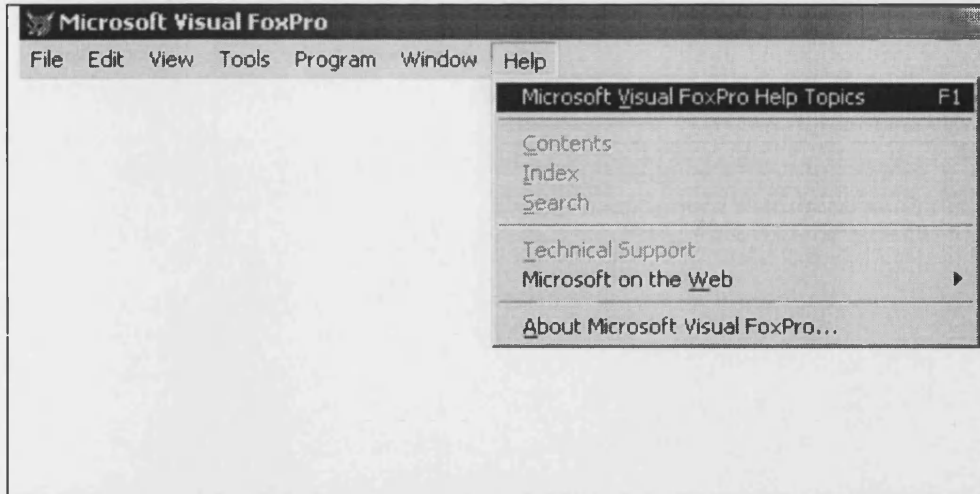


Figure B.3: Visual FoxPro Help Program

B.6 Accessing Data in Tables

There are countless ways to use or manipulate data in tables, but first it is necessary to access the tables.

The Data Session window provides the most effective way of accessing tables. Each table opens its own data session. The menus or code can be used to move from session to session, opening and viewing tables, with two menu selections or commands for each table. However, if Data Session window is used, it is possible to open all the tables (to the limit of installed memory) without closing the window. The Data Session window also provides information on table properties and any relationships might be set up between tables

To clear the data environment:

1. In the **Command** window (figure B.4), type the following:

```
CLOSE ALL TABLES
```

2. Press **ENTER**.

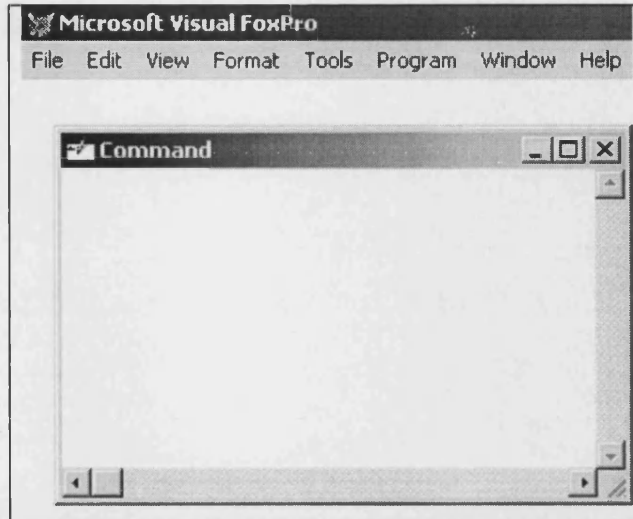


Figure B.4: Visual FoxPro command Table

To view table properties:

1. From the **Window** menu, select **Data Session**.
2. In the **Data Session** window, select a table (figure B.5).
 - If a table is already open, it is listed in the Aliases drop-down box so it is selectable.
 - If no table is open, click **Open** to access the **Open** dialog box, which makes it possible to specify which table to open.
 - If the listed table is in a database click **Open**, the **Open** dialog box displays a list of the other tables in that database. Then it is possible to select one from the list or click the **Other** button to specify a free table.

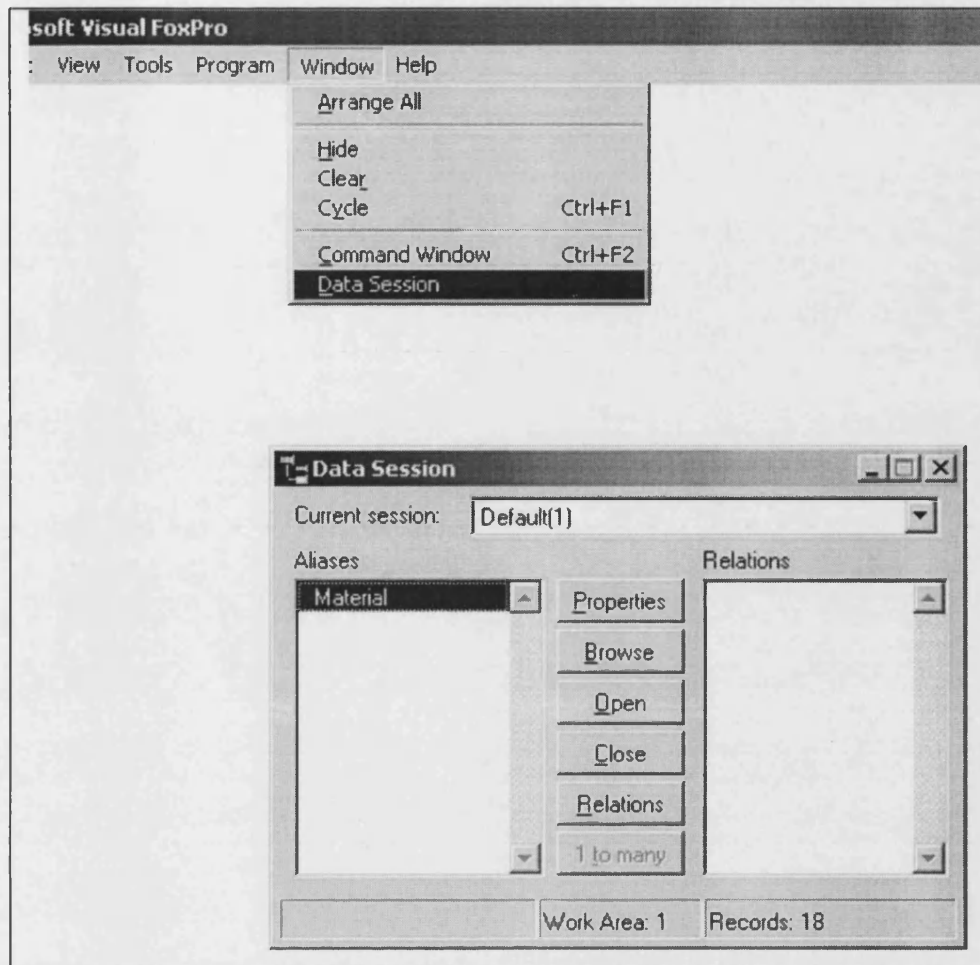


Figure B.5: Visual FoxPro Data Session

To access a table for viewing or editing:

- In the **Data Session** window, select an open table, and then click the **Browse** button. It is possible to continue until all the listed (open) tables are displayed.

Note Each time a table browses in the **Data Session** window, the Command window displays a new **SELECT** statement followed by a **BROWSE** statement.

To view and modify Table characteristics:

- In the **Data Session** window, it is necessary to select an open table, and then click the **Properties** button. This opens the **Work Area** dialog box, which provides information and access to the table structure and indexes.

In this environment, it is possible to select any table and edit it, append and delete records, or modify the table structure.

When it opens, it is possible to navigate the table, change or delete record contents, or add new data. It is necessary to use View menu options to select the type of access. To navigate or modify the table it is necessary to use the Table menu options. More information on using tables, is shown in "Working with Tables" in the Visual FoxPro Help and more information on the Data Session window, is accessible in "Using Data Sessions" in the Visual FoxPro Help.

Computer cost estimation at the concept design stage

H. Hosseini-Nasab, L. B. Newnes and A. R. Mileham

Department of Mechanical Engineering
University Of Bath
Bath BA2 7AY

Summary

The concept stage of design is characterised by a low level of product definition and detail. However it is at this stage that a large proportion of the avoidable costs are typically created. There is a need for designers with limited process knowledge; to estimate product costs at the conceptual stage with reasonable accuracy. The paper compares 11 published early cost estimating methodologies each of which have been applied to just the one process. It also discusses the problems and advantages of each method and their claimed accuracies. Most importantly each method is evaluated with regard to its general applicability and use in a comprehensive cost estimating system for use during the concept design stage.

1. Introduction

Designers are mainly concerned with functionality, aesthetics, costs, quality and manufacturability. At the concept stage of design there is usually concentration on the intellectually challenging task of creating functionality that conforms to the design specification. It is claimed that the accuracy of a cost estimate improves with the volume of information available [1] and as only basic information is available at the conceptual design stage, cost estimating tends to be inaccurate and of low priority. Paradoxically, it is also at the conceptual design stage that, the majority of the unavoidable costs are locked into the product and up to 50% of the avoidable costs are also generated [2]. As the design cycle proceeds projects accumulate man-hours of design effort and gain a momentum that makes them increasingly difficult to abort. If after the detailed stage, designs are found to be too expensive, the course of action many companies take is to try to reduce manufacturing costs and/or use different materials etc, rather than to redesign out the avoidable costs. The likely consequence of this policy is typically a reduction in both cost and quality. The costing information available at the conceptual design stage usually takes the form of historic product costs. The usefulness of this information depends on the degree of similarity between the old and new products and the time gap between the designs. If no similar historic costs are available then either an "experienced guesstimate"

can be made or as is more likely the cost estimate is deferred until more information is made available, towards the design finalisation stage.

At present, manufacturing companies are moving towards a system of concurrent or simultaneous engineering in order to improve competitiveness. Concurrent engineering reduces lead time by carrying out manufacturing systems design in parallel with product design and for this to be effective it is necessary to design the product "Right-First-Time" in all aspects including costs. In this environment there is a growing need to provide the designer with a simple, accurate method of estimating product costs during the conceptual stage of design.

2. Conceptual Information

At the conceptual stage the design of a component is typically in sketch form and the information describing it is limited. For an injection moulded component [3] the information available typically consists of the general material type, e.g. ABS, Nylon, etc, the production volume and the product's general size, form and main features, (for example its maximum section thickness). The designer may not be familiar with the manufacturing processes that will be used to convert the raw material into the finished product. If this is the case there will also be a lack of understanding of which component parameters significantly influence cost. This is particularly so in companies wishing to incorporate a process into their designs for the first time. In all cases process knowledge is a critical element in formulating the cost estimate and must be incorporated in some way.

3. Comparison of Current Early Cost Estimating Methods

This paper looks at the methodologies that have been used by researchers who have attempted to develop early cost estimating systems. They are virtually all process specific methods that require low level, process specific information to produce an estimate, rather than methods that use higher order information.

(i) *Decision tables* - A decision table is a symbolic way of representing the logical interdependence between events in a simple tabular form [4]. A set of tables can be established that link product attributes to relevant costs and once constructed they can be used for cost estimating. This method is easy to understand and use but the method requires a significant amount of expert knowledge to be elicited for the tables to be set up. It is thus a process specific method. The accuracy of the method is highly dependent on the quality of the expert knowledge but has been claimed to be within 80%.

(ii) *Fuzzy sets* - In the cost estimation process, there are known physical/engineering variables with definite values and there are probabilistic/random variables, such as labour fatigue rates, resource shortages, machine failure, etc which can not be accurately predicted [5]. This uncertainty can be incorporated into a cost estimating system by using fuzzy sets that have both deterministic and probabilistic variables as inputs. The cost estimation then can be obtained from the fuzzy set output variables. Almost all known cost factors can thus be included in the fuzzy sets and this is considered to be an advantage, but since the cost estimation involves uncertainty, it is necessary to output a range of possible costs. If the process specific input information can be obtained, and this again is considered difficult, then it is claimed to produce a reliable cost estimate.

(iii) *Time scale* - Processing and assembly times themselves give a good indication of the product cost and these have been used to assist the designer to

estimate costs at the design stage [6]. To do this the hourly production rates for equipment and labour are derived and then built into semi-parametric equations. It is considered to be applicable to very simple situations for which it is fast and reliable. However its application is limited, the process specific information is difficult to obtain at the conceptual design stage and it is thus more applicable to the latter stages of design.

(iv) *Activity based cost* - In the activity-based cost estimating method, the main input for cost estimating is the consumption of resource [7]. For this method the primary design attributes and support related attributes that affect the final cost of the product are used to derive cost estimating equations. Again, a semi parametric approach is used. Although relevant historical cost data was available for the research on this method to be conducted, it was still necessary for an extensive study of the primary design attributes to be carried out. It is claimed to be general solution that produces a reliable estimate.

(v) *Bottoms-up* - The bottoms-up approach is similar to the time scale approach. The times needed to produce each part are calculated along with the hourly rates for machinery and labour [8]. The times and rates are then multiplied to get the processing costs. To estimate the product cost, indirect/overhead costs are then added. Although this was put forward as a "design stage" method it is not considered to be applicable for early cost estimating as it requires considerable design detail to function.

(vi) *Feature based costing* - In many cases, the product geometry directly affects product costs, and can be considered as cost drivers for cost estimating. If the features that affect product cost can be identified at the early design stage they can be used, via equations, as the basis of a cost estimating method [9]. Again this is a semi-parametric approach. The method is generic and flexible but process specific information is required that is experienced based and its quality can significantly affect the accuracy of the estimate.

(vii) *Parametric method* - Parametric cost estimating system utilise the empirical relationships between cost parameters and selected physical properties or performance parameters of the product [3]. The parametric method reflects these relationships in the form of mathematical equations which can then be used to estimate product cost. Minimum component information and little or no experience for cost estimating are the main advantages but identifying the equations requires experience and significant amounts of historic cost data. It is capable of producing estimates that have an accuracy of at least 80%.

(viii) *Group technology* - The group technology method is based on the principle of product similarity and uses a family cost value that is modified by the actual components real size, complexity, etc [10]. In this research simple linear relationships were used to link the final cost and the variable cost factors. The method is easy to use if a group technology system is in use.

(ix) *Cost estimation by comparison* - Comparing a new product with similar existing products can be the basis for a cost estimate of the new products. The comparison can be based product features, complexity or the method of manufacture [11]. Allowances can be made to account for any difference between new and existing products. A fast cost estimate is the result but the accuracy is related to the level of product similarity.

(x) *Neural networks* - The cost of a new product can be estimated using neural networks in two stages [12]. In the first stage a knowledge base of existing products and their historical cost is built up. In the second stage, the cost of the new product is estimated

by comparing the new design specification with the knowledge base information. An advantage is that virtually all cost aspects can be incorporated but as with most other methods, the accuracy is dependent on the availability of good historical cost data.

(xi) *Expert system* - An expert system, in the form of either a computer program or a narrative procedure contains a domain specific knowledge base and a set of rules [13]. The expert system can be used to generate a cost estimate from product input data which chains through the rules until a conclusion is reached. Expert cost knowledge can be obtained from a variety of sources but it is difficult to elicit accurately and to generate rules from it. Such systems are process specific but can be used by non experts to produce early estimates of reasonable accuracy.

4. Conclusions

Several methods have been put forward for cost estimating at the early stage of design. The majority are process specific and require considerable amounts of cost, process and product information and time to set up. Although researchers claim that the methods are generic and thus capable of expansion none of the methods reviewed have in fact been expanded because of the difficulties involved. None of the methods reviewed contain both a high level rough cut estimate and a lower level process specific estimate although this would have considerable advantage for cross process comparisons at the early design stage.

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13. K. S. Chin and T. N. Wong, "An Expert System For Injection Mould Cost Estimation", Adv. Polymer Technology, 1995, Vol. 14(4), pp 303-314.

Figure 1 Comparative Table of Cost Estimating Methods.

	Method	Where Used	Advantages	Limitations	Accuracy
1	Decision tables	Injection mould company	Using technical data, easy to understand and use	Needs expert knowledge and historical data	80%
2	Fuzzy sets	Flat plate processing	Can use almost all the cost influencing factors	Inherently uncertain	Reliable range
3	Time scale	Tack welding, sawing, guillotining	Fast and easy for cost estimating	Could not be use for complex process	Reliable
4	Activity based cost	General	Uses direct and indirect historical cost data	Needs significant historical data to function correctly	Unknown
5	Bottoms-up	Turned component products, machined components	Flexibility, no need for one or more existing products	Need expert and experience for using information correctly	Reliable
6	Feature based costing	Injection moulding	The cost estimation can accommodate shape changes	Results highly dependent upon experience	Reliable
7	Parametric method	Composite materials, Injection moulding	Minimum component information needed, easy to use	Identifying equations that relate features and costs	80%
8	Group technology	Injection moulding	Fast and easy cost estimates	Simple linear relationship between the final cost and the variable cost factors	Low
9	Cost estimation by comparison	STS Orbiter development	Simple cost estimating	New and existing product must be similar. Historical data required	Reliable If data available
10	Neural networks	Packaging products	Looks at overall cost.	Accurate historical data and experience required	Reliable If data available
11	Expert system	Printed circuit boards, Casting, Injection moulding	Uses many cost drivers. Fast interactive evaluation,	Takes time to create the system. Derivation of rules difficult	Reliable If data available