De Montfort University
Faculty of Computing Sciences and Engineering

AN INTELLIGENT KNOWLEDGE BASED COST MODELLING SYSTEM FOR INNOVATIVE PRODUCT DEVELOPMENT

ESAM MAHMOUD SHEHAB

PH.D THESIS

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ABSTRACT

Keywords: *Cost Modelling, Knowledge-Based System, Design for Automation, Concurrent Engineering, Process Optimisation, Fuzzy Logic, Machining and Injection Moulding Processes, Innovative Product Development Process.*

This research work aims to develop an intelligent knowledge-based system for product cost modelling and design for automation at an early design stage of the product development cycle, that would enable designers/manufacturing planners to make more accurate estimates of the product cost. Consequently, a quicker response to customers' expectations. The main objectives of the research are to: (1) develop a prototype system that assists an inexperienced designer to estimate the manufacturing cost of the product, (2) advise designers on how to eliminate design and manufacturing related conflicts that may arise during the product development process, (3) recommend the most economic assembly technique for the product in order to consider this technique during the design process and provide design improvement suggestions to simplify the assembly operations (i.e. to provide an opportunity for designers to design for assembly (DFA)), (4) apply a fuzzy logic approach to certain cases, and (5) evaluate the developed prototype system through five case studies.

The developed system for cost modelling comprises of a CAD solid modelling system, a material selection module, knowledge-based system (KBS), process optimisation module, design for assembly module, cost estimation technique module, and a user interface. In addition, the system encompasses two types of databases, permanent (static) and temporary (dynamic). These databases are categorised into five separate groups of database, Feature database, Material database, Machinability database, Machine database, and Mould database.

The system development process has passed through four major steps: firstly, constructing the knowledge-based and process optimisation system, secondly developing a design for assembly module. Thirdly, integrating the KBS with both material selection database and a CAD system. Finally, developing and implementing a fuzzy logic approach to generate reliable estimation of cost and to handle the uncertainty in cost estimation model that cannot be addressed by traditional analytical methods.

The developed system has, besides estimating the total cost of a product, the capability to: (1) select a material as well as the machining processes, their sequence and machining parameters based on a set of design and production parameters that the user provides to the system, and (2) recommend the most economic assembly technique for a product and provide design improvement suggestion, in the early stages of the design process, based on a design feasibility technique. It provides recommendations when a design cannot be manufactured with the available manufacturing resources and capabilities. In addition, a feature-by-feature cost estimation report was generated using the system to highlight the features of high manufacturing cost. The system can be applied without the need for detailed design information, so that it can be implemented at an early design stage and consequently cost redesign, and longer lead-time can be avoided. One of the tangible advantages of this system is that it warns users of features that are costly and difficult to manufacture. In addition, the system is developed in such a way that, users can modify the product design at any stage of the design processes. This research dealt with cost modelling of both machined components and injection moulded components.

The developed cost effective design environment was evaluated on real products, including a scientific calculator, a telephone handset, and two machined components. Conclusions drawn from the system indicated that the developed prototype system could help companies reducing product cost and lead time by estimating the total product cost throughout the entire product development cycle including assembly cost.

Case studies demonstrated that designing a product using the developed system is more cost effective than using traditional systems. The cost estimated for a number of products used in the case studies was almost 10 to 15% less than cost estimated by the traditional system since the latter does not take into consideration process optimisation, design alternatives, nor design for assembly issues

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Esam Mahmoud Shehab

This Thesis is dedicated to the

Spirit of my Parents

of Whom I am the Fruit of

their Effort and Struggle

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NOMENCLATURE

SYMBOLE	DEFINITION
AF	Automatic Assembly using Free Transfer Machines
AI	Artificial Intelligence
AP	Automatic Assembly with Programmable Workheads
AR	Robotic Assembly using Single Arm Robot
BHN	Brinel Hardness Number
B-rep	Boundary Representation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CE	Concurrent Engineering
CMS	Cambridge Materials Selector
C_{mt}	Cost of Material
CNC	Computer Numeric Control
CSG	Constructive Solid Geometry
DFA	Design for Assembly
DFM	Design for Manufacturing
EDM	Electric Discharge Machining
ES	Expert System
FBM	Feature Based Modelling
GAs	Genetic Algorithms
GT	Group Technology
IPD	Integrated Product Development
KBS	Knowledge-Based System
KEE	Knowledge Engineering Environment
LBM	Laser Beam Machine
LCC	Life Cycle Cost

MM	Manual assembly with Mechanical Assistance
NN	Neural Networks
OOP	Object-Oriented Programming
PCB	Printed Circuit Board
PDP	Product Development Process
QFD	Quality Function Deployment
SMEs	Small Medium Enterprises

CHAPTER 1

1 INTRODUCTION

1.1 General

In modern manufacturing systems, high product quality, manufacturing flexibility, and low production cost are essential keys to competitiveness. For this reason, manufacturing cost is always an item of primary concern. Today many companies, all over the world, have given up utilising the traditional product development approach to avoid product failure, loss of sales and profit, and declining market share. Successful product development now requires fundamentally improved methodologies for the organisation of the product development process, to reduce waste and to design products in order to meet customer requirements to respond to the global competition. Concurrent Engineering (CE) is one of the techniques, which can be used to achieve the above objectives.

CE as a technique could be used to achieve and sustain a competitive advantage through the design of low cost and high quality products, by the implementation of an integrated product and process development approach including various life cycle requirements such as material, processes, design requirements, optimisation, and manufacturability. The success of the CE approach is subject to the careful consideration of product life cycle issues at the early stages of the design process. This helps to eliminate high risk and cost.

Generally, designers have little access to cost information and therefore have limited control over the product cost, although their decisions have impact effects on the cost of a product. This is partially because the amount cost information is insufficient and the format is unsuitable. Therefore, designers need a cost estimation tool to overcome the above limitation.

The most important step of cost estimation is the construction of cost models that can derive meaningful cost estimates based on the collected data. The model required to track costs in a CE environment is different from the usual models for estimating product costs, because the traditional cost estimating systems are not constructed adequately to support CE. An integrated cost estimating system is required to adhere to and enhance the CE philosophy (Jo et al (1993)).

1.2 Motivation for Product Cost Estimation

Motivation for professional engineering cost estimation results from the necessity for profits, stewardship of resources, and competition. There is no doubt that, reducing the cost of a product at the design stage is more effective than at the manufacturing stage. Therefore, if the product manufacturing cost can be estimated during the early design stage, designers can modify a design to achieve proper performance as well as a reasonable cost at this stage and encouraging designers to design to cost.

The major concept of concurrent engineering (CE) is to put the majority of effort in the product design stage to analyse the factors, which might affect subsequent production process. One of the targets of CE philosophy is to reduce the manufacturing costs.

To ensure maximum productivity, it is necessary to have an accurate cost estimation of the product. According to the Society of Cost Estimating and Analysis (SCEA), cost estimating can be defined as “the art of approximating the probable worth or cost of an activity based on information available at the time” (Steward, (1991)). In addition, the difference between the estimated cost and the actual cost is that only the most important factors are considered in an estimation process (Ouyang et al (1997)).

The cost of the design process constitutes a small proportion of the total product cost. It accounts for only 6% of the total development cost, (Hundal (1993), Nevins and

Whitney (1989), Shehab and Abdalla (2001b), Asiedu and Gu (1998), and Jo et al (1993)). However, a large portion of the manufacturing cost is determined in the design phase of product development. Research results show that over 70% to 80% of the production cost of a product is determined during the conceptual design stage (Bedwart et al (1991), Hundal (1993), Mirakon et al (1993)). The remaining 20% to 30 % of the cost is determined during the actual production. Therefore devoting a greater effort to design to cost is a reasonable and necessary step towards optimising product costs. Figure (1.1) illustrates the percentage of product costs set and incurred in different phases.

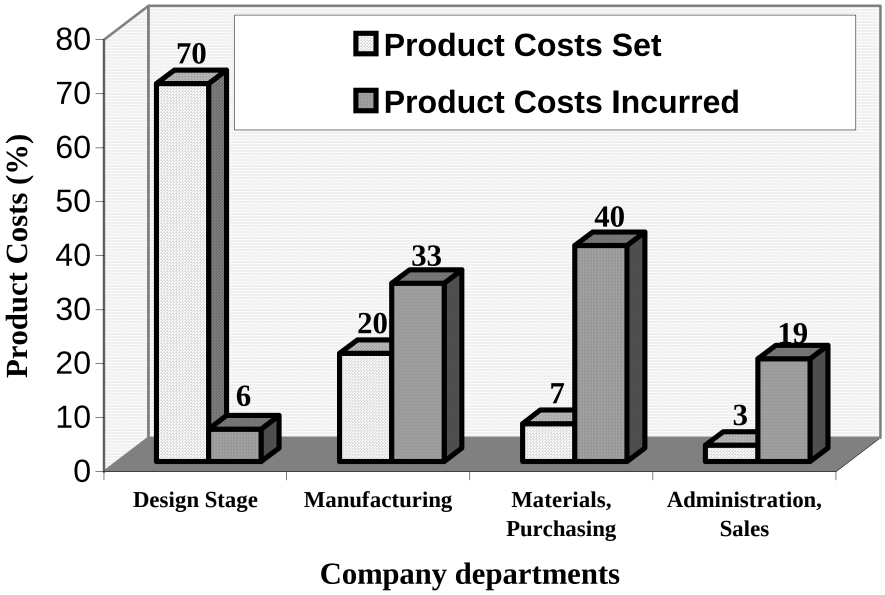


Figure (1.1) Percentage of Product Costs Set and Incurred in Different Phases (Hundal (1993a))

1.4 Aims and Objectives of the Thesis

The main aim of this thesis is to develop an integrated knowledge-based system for product cost modelling at early design stage of the product development cycle that enables designers/manufacturing planners to make more accurate estimates of costs involved in various stages of the product development. Consequently quicker response to customers' expectations is generated.

The main objectives of this research are to:

- Develop a methodology for modelling product costs at an early design stage.
- To develop a prototype system that assists an inexperienced designer to estimate the manufacturing cost of the product.
- Integrate the system with the CMS, to facilitate the material selection process. The system should able to retrieve the component envelope dimensions and its volume from the database of the CAD system.
- Advise designers on how to eliminate design and manufacturing related conflicts that may arise during the product development process.
- Recommend the most economic assembly technique for the product in order to consider this technique during the design process and provide design improvement suggestions to simplify the assembly operations. (i.e. to provide an opportunity for designers to design for assembly (DFA)).
- Enable designers/manufacturing planners to reduce unnecessarily downstream manufacturing costs thus reducing total product cost and product lead-time.
- Develop and implement a set of fuzzy logic models to deal with uncertainty in the knowledge of cost model in order to generate reliable cost estimation.
- Demonstrate the capabilities of the developed system via five case studies.

1.5 Layout of the Thesis

The remainder of the thesis is divided into seven chapters (see Figure (1.2)). In **chapter 2**, a comprehensive survey of previous work in various areas related to this research is presented. It is divided into several sections, such as concurrent engineering, cost structure and cost models.

Chapter 3 describes the proposed system design structure and characteristics for estimating manufacturing costs at an early design stage. It also provides a description of the elements of the proposed approach. A working scenario for the developed system is described in this chapter.

Cost Modelling for both machining and injection-moulding processes is addressed in **Chapter 4**. The various knowledge representation techniques, used in the developed system, are presented. A fuzzy logic model for cost estimation is discussed. In addition, this chapter outlines the factors considered for cost estimation of an injection moulded component.

Product assembly cost estimation and design for automation are discussed in **chapter 5**. The basic factors used in selection of the most economic assembly technique are explored in this chapter.

Case studies are presented and discussed in **chapter 6** to demonstrate the capabilities of the system and the significance of this research.

In **chapter 7**, conclusions are drawn and the overall benefits of implementing the system explained. Finally, recommendations for future work are explored in **chapter 8**.

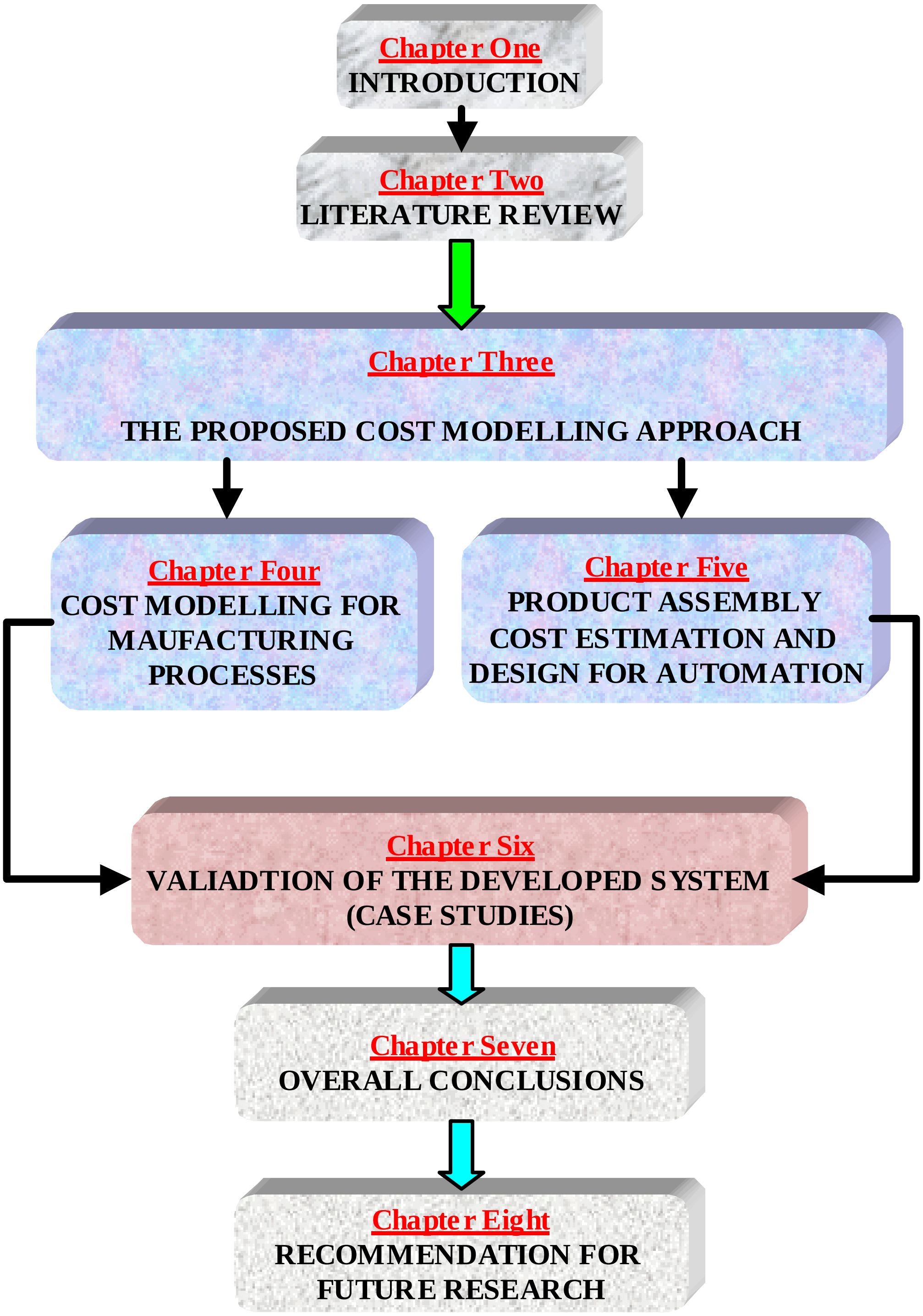


Figure (1.2) Thesis Outline and Structure

CHAPTER 2

2 LITERATURE REVIEW

2.1 <u>Introduction</u>

Product cost estimation is a vital concern of every manufacturing enterprise, because it is helpful in the design of new products to make sure that targeted costs are met and competitive prices can be achieved (Ping et al, 1996). The estimation of manufacturing cost, during the early design stage, is one area that has been given little attention by researchers. However, most of the research work in this area has estimated costs at the design phase using mathematical modelling and empirical formulae as the primary tools.

In this chapter, the previous work available in the literature concerning this area of research is reviewed. The system framework and general procedure are outlined for each study. The chapter structure and outline is illustrated in Figure (2.1).

The organisation of the rest of this chapter is as follows. The next section presents definitions, principles, and research work in the area of product development process and quality deployment development (QFD). In Section 2.3 a definition of concurrent engineering and reviews of research work in the area of concurrent Engineering are presented.

Section 2.4 explores an overview of the cost structure. Section 2.5 outlines the various approaches for cost estimation. Section 2.6 reviews the previous cost models for various manufacturing processes. A review of research work in the area of computer aided process planning (CAPP), design for assembly (DFA), fuzzy logic, neural networks, and

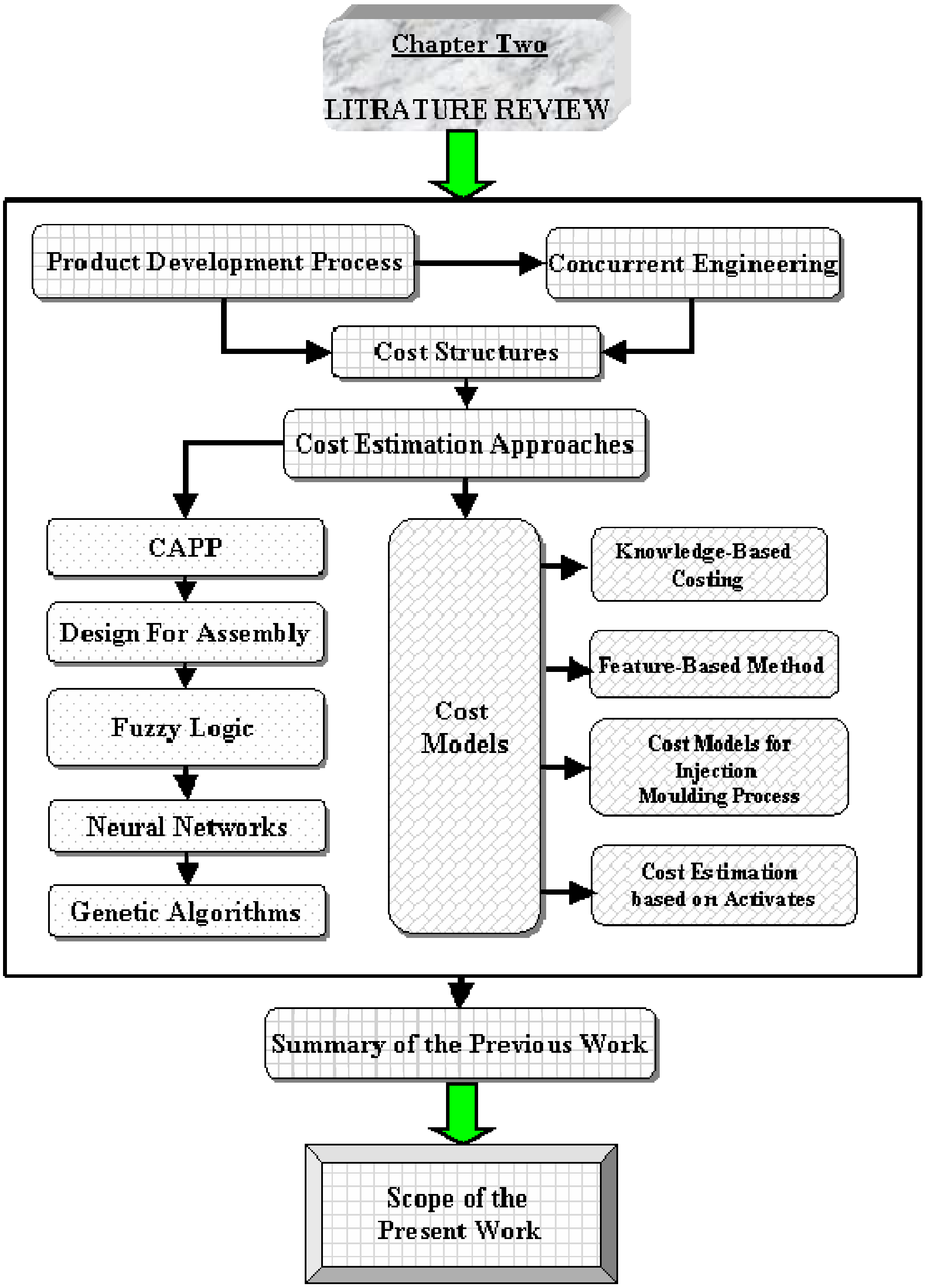


Figure (2.1) The Structure and Layout of Chapter Two genetic algorithms is given in Sections 2.7, 2.8, 2.9, 2.10, and 2.11 respectively. Finally, a critical appraisal of the previous research work and scope of the present work are presented in Section 2.12 and Section 2.13, respectively.

2.2 Product Development Process (PDP)

The steps involved in successfully bringing a new product to the market are product evaluation, development planning, product design, prototyping and marketing. Product definition is a critical starting point in the development of any new product (Crow (2001)).

The goal of an integrated product concepts development is to improve the effectiveness and efficiency of product concepts development and evaluation (Chin and Wong (1999)). The objectives of Integrated Product Development (IPD) are:

- The design of products to better meet customer needs and quality expectations
- The design of processes or the consideration of process capabilities in designing products in order to produce products at a more competitive price
- Reduction of product and process design cycle time or time-to-market to bring products to market earlier
- High productivity through release of producible designs and minimization of disruptive design changes

The principles of integrated product development are as follows (DRM (2001)):

1. **Understand customer and manage requirements.** Better customer relationships, frequent communication, and feedback systems lead to better understanding the customer's/user's needs. Methodologies such as Quality Function Deployment (QFD) aid in defining customer needs and translating those needs into specific product, process and quality requirements.
2. **Plan and manage product development**.
3. **Use product development teams.** Early involvement of marketing/ program management, manufacturing, material, test, quality, and product support personnel in

product development provides a multi-functional perspective and facilitate the parallel design of product and process, reducing design iterations and production problems.

4. Integrate process design. The design of manufacturing and product support processes must be integrated with the design of products in order to optimise the performance, availability and life cycle cost of the product.

5. Manage costs from the start. This can be achieved by: (1) developing a greater awareness of affordability and life cycle costs, (2) establish target costs and manage to those targets, and (3) managing non-recurring development costs by effective planning; incremental, low-risk development; and managing project scope.

6. Involve suppliers and subcontractors early. Suppliers know their product technology, product application, and process constraints best. Utilise this expertise during product development and optimise product designs to the capabilities of the "virtual factory" which includes these suppliers.

7. Develop robust designs. Quality engineering and reliability techniques such as Design of Experiments, provide an efficient way to understand the role and interaction of product and process parameters with a performance or quality characteristic leading to robust designs and enhanced reliability.

8. Integrate CAE, CAD & CAM tools. These tools, when intelligently and cost effectively applied, can lead to a streamlined development process and project organisation.

9. Simulate product performance and manufacturing processes electronically. Analysis and simulation tools such as FEA, circuit simulation, thermal analysis, NC verification and software simulation can be used to develop and refine both product and process design inexpensively. These tools should be used early in the development process to develop a more mature design and to reduce the number of time-consuming design/build/test iterations for mock-ups and developmental prototypes.

10. Create an efficient development approach. Align policies, performance appraisal, and reward systems to support these development objectives and team-based approaches.

11. Improve the design process continuously. Continued integration of technical tools, design activities and formal methodologies will improve the design process. Use benchmarking as an objective basis for comparing the organisation and its products to other companies and their products and identifying opportunities for improvement.

Chang et al (1999) presented three concepts and methods for product development: (1) brining product performance, quality and manufacturing cost together in the early design stage, (2) supporting design decision-making through a quantitative approach, and (3) incorporating rapid prototyping for design verification through physical prototypes.

Chin and Wong (1999) proposed an integrated product concepts development and evaluation framework. The aim of the developed framework was to guide product designers to have a thorough exploration and evaluation of alternative product concepts.

Fan (2000) developed an integrated model of information flow according to product development process stages and functional skills involvement in CE. The developed model could be used as a basis for planning the human resources, analysis tools, and information technology communication tools needed in new product development.

2.2.1 Quality Function Deployment (QFD)

Quality can be defined as meeting customer requirements and providing superior value. This focus on the customer places an emphasis on techniques such as Quality Function Deployment to help understand customer needs and provide superior value (Crow (2001).

Quality Function Deployment (QFD) is a structured approach to defining customer needs or requirements and translating them into specific plans to produce products to meet those requirements. This understanding of the customer requirements is then summarized in a product planning matrix or "house of quality". These matrices are used to translate higher level "what's" or requirements into lower level "how's" or means to satisfy the requirements.

QFD is an extremely useful methodology to facilitate communication, planning, and decision-making within a product development team. QFD is oriented toward involving a team of people representing the various functional departments that have involvement in product development: Marketing, Design Engineering, Quality Assurance, Manufacturing/ Manufacturing Engineering, Test Engineering, Finance, Product Support, etc.

The structure of this methodology helps development personnel understand essential requirements, internal capabilities, and constraints and design the product so that everything is in place to achieve the desired outcome - a satisfied customer. QFD helps development personnel maintain a correct focus on true requirements and minimises mis-interpreting customer needs.

The basic QFD methodology involves four basic phases that occur over the course of the product development process. These phases are product planning, assembly/component deployment, process planning, and process/quality control.

The product plan helps resolve issues related the markets, the types of products and the opportunities that the company will invest in and the resources required to support product development. More specifically, the product plan is used to:

- Define an overall strategy for products to guide selection of development projects;
- Define target markets, customers, competitive strengths, and a competition strategy (e.g., competing head-on or finding a market niche);
- Position planned products relative to competitive products and identify what will differentiate or distinguish these products from the competition;
- Rationalise these competing development projects and establish priorities for development projects;
- Provide a high-level schedule of various development projects; and
- Estimate development resources and balance project resource requirements with a budget in the overall business plan.

Downlatshahi and Ashok (1997) presented a methodology for the integration of QFD and Design of Experiment (DOE) in a concurrent engineering environment. They suggested that the proposed approach could lead to improved process, shorter lead – time and less product cost.
Concurrent Engineering (CE) has been used to support the product development process. The following section will present the concepts of CE philosophy.

2.3 Concurrent Engineering

As illustrated in the previous section, the product development cycle begins with a need conception based on market analysis and research and development (R&D) activities. Conventionally, a series of sequential steps is followed to design the product. The traditional way of engineering has been of a sequential nature, in which each activity concerned with the product development is carried out in isolation from other activities. In other words, each activity being thrown 'over the wall' to the next downstream activity or ' we design it – you make it'. The sequential order leads to poor manufacturing system design from global product development perspective and consequently leads to a lack of competitiveness. Therefore, a new integrated product design approach needs to be developed in order to deal with this problem.

Concurrent Engineering (CE) is defined as a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This is in stark contrast to the traditional engineering approach. CE is a modern product development philosophy rather than a technology aiming at shorter lead times, higher quality, lower costs, and consideration of the total life cycle of the product related features in the earlier stage of design/development including not only the specific function of product but also manufacturing, assembly, inspection, and service availability. Koufteros at al (2001) stated that CE is a mechanism that can reduce uncertainty and equivocality in the product development arena and improve an organisation's competitive capabilities. An example of the concurrent engineering wheel is illustrated in Figure (2.2) (Jo et al (1993)).

There are two basic approaches for implementing concurrent engineering namely: team-based and computer-based approaches (Jo et al (1993)). The former approach is human-oriented, in that the team consists of designers and individuals from all other related functional areas. A number of computer-based environments have been developed to support CE, such as Abdalla (1998), Pham and Ji (1999) and Gayretli and Abdalla (1999).

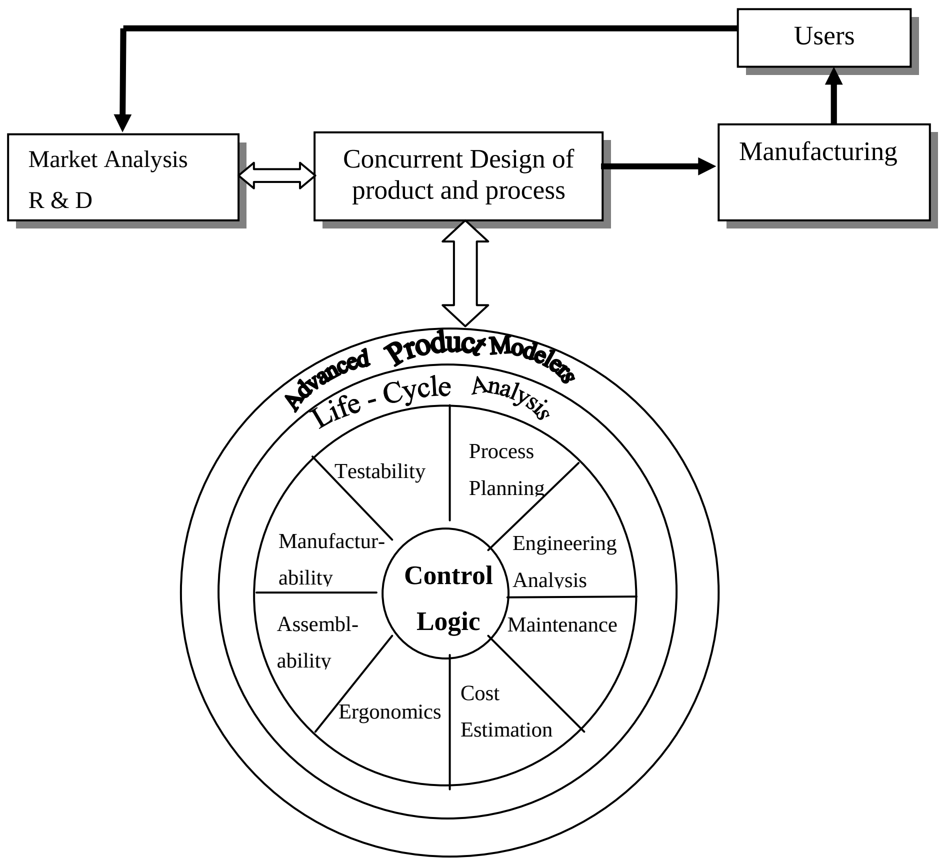


Figure (2.2) Product Development Cycle Employing Concurrent Engineering Strategy (Jo et al (1993))

The goal of Concurrent Engineering is to improve the interactive work of different disciplines affecting a product. The following are some of the benefits of implementing CE (Smith et al (2001)):

a) Minimising the product life cycle - Eliminating the redesign procedure,
b) Decreasing production cost - resulting from the minimising of the product life cycle,
c) Maximising product quality - By spending more time and money initially in the design cycle and ensuring that the concept selection is optimised, so that a company can increase the prospect of delivering a quality product to the customer,
d) Teamwork - Human Resources are working together for a common product.

Abdalla (1999) summarised the tangible benefits of implementing of CE in that it improves communication, quality, less design changes, shorter time to market, reduced development cost, effective management, and increasing profit.

An approach to concurrent engineering, which focused on simultaneous product design and process planning, has been presented by Pham and Dimov (1998). The approach provided a natural way for conveying manufacturing information to the designer. The goal of this approach was to produce tools to assist designers in taking downstream manufacturing issues into consideration early in the design process in order to minimise costly iterations.

2.4 <u>Cost Structures</u>

A cost structure can be described by cost elements or components and cost relationships. Cost elements or a cost relationship can be described in terms of ‘cost drivers’ or ‘attributes’. Sheldon et. al. (1991) classified cost structures into the following forms:

Organisation breakdown. The organisation of a company can be broken down into a number of departments, which in turn can be further broken down into sections and so on. This organisational structure can be used as a cost structure that depicts the cost distribution among different units within the company. This breakdown is also known as responsibility breakdown.

Generation breakdown. A product can usually be broken down into components that in turn can be broken down into elements. This kind of product structure can be used as the cost structure for estimating total cost by recursively summing up costs associated with constituent components.

Functional breakdown. Another practice of generation breakdown is on the basis of functionality within a product. The product can be broken down into constituent functions. This functional generation breakdown structure can be used by designers to estimate product cost at fairly early stages, such as the conceptual design stage.

Work breakdown. Work breakdown is similar to generation breakdown. However, it places emphasis on the activities involved in producing a product. It is the basis of the activity-based costing (ABC) method.

2.5 Cost Estimating Approaches

Cost can be employed as an evaluation criterion in design in two ways. It can be used either in a design-to-cost or design-for-cost context. Design-for-cost is not design to cost (Dean and Unal (1992)). It is the conscious use of engineering process technology to reduce life cycle cost while design-to-cost obtains a design satisfying the functional requirements for a given cost target. Design for cost is an engineering driven process. Design to cost is a management driven process (Dean and Unal (1992)). Design for cost seeks to design the product once and only once. Design to cost is iterative by nature and hence incurs redesign and rework cost.

In general, cost-estimating approaches can be broadly classified as intuitive method, parametric techniques, analogue (estimating by analogy), and analytical models. The intuitive method is based on the experience of the estimator. The result is always dependent on the estimator’s knowledge.

Parametric estimating, is the generation and application of mathematical algorithms that describes relationships between cost schedules and measurable attributes of a system (Dean (1995)). Cost estimation with a parametric model is based on predicting a product's (or component's) cost either in total or various activities, e.g. design or manufacture, by the use of regression analysis based on historical cost and technical information. It is often referred to a top-down estimating technique. The drawback of this approach is that it is not very good for estimating the cost of products that utilise new technologies. Also, the parametric method functions like a “black box”. In this case, it is very difficult to understand important elements of the manufacture and to be able to justify results.

Dean (1995) has shown that the concepts of parametric cost analysis and optimisation can be integrated into cost deployment to create a process that approaches this goal. He also proposed a framework for such combined process, which is named parametric cost deployment.

Mileham et al (1993) developed a parametric model for estimating the cost of injection moulded components. The approach is useful and early cost estimates can be made based on the weight of the component alone. Comparison of two methods for economic evaluation of mechanical design including, a parametric method and an analogue method, have been presented by Duverlie and Castelain (1999). This analogue method used case-based reasoning, which is a particular type of analogy.

Cost estimating by an analogue technique is based on the similarities between a new product and a previously manufactured product. The cost of the product features is calculated using heuristic data of similar products from same family. Thus, it is mainly used with group technology (GT). The main disadvantage of estimating by analogy is the high degree of judgement required. The implementation of this method necessitates significant investment, which is not always compatible with the size of the enterprise, which are often Small Medium Enterprises, SMEs (Duverlie and Castelain (1999)).

A detailed (analytical) model uses estimates of labour time, material quantities and prices to estimate the direct costs of a product or activity. It allows us to obtain manufacturing process that can be easily adapted to the workshop context. The slowness of the method is a problem, which makes it unpopular with estimators. These models are shown in Figure (2.3). These methods cannot be used during the whole life cycle. Some methods are better than others depending on the context (Duverlie and Castelain (1999)). For example, some costs, such as set-up costs, are well suited to the analogue method while a parametric method is preferred to estimate the raw material cost of a component, for example. However, the most accurate cost estimates are made using the analytical approach.

According to Stewart (1991) four basic tools are required for estimating the product or project cost, information, methods, schedule and skills. Every cost estimate must be based on complete, thorough, and current information concerning the process, product, project, or service being estimated. This information takes many forms, among them drawing, specifications, and manufacturing plans. Before starting to develop a cost estimate, a decision must be made concerning the estimating method or combination of methods to be used. The method chosen depends mainly on the time allotted to prepare the estimate and the accuracy and depth of penetration of rationale required.

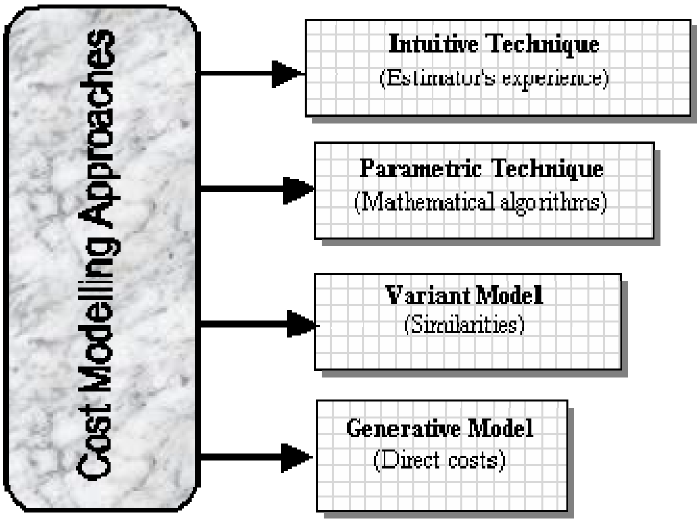


Figure (2.3) Various Techniques of Cost Modelling

A number of different skills are needed in the preparation of a cost estimate. These skills may be possessed by one person or by an organisation, so it is necessary to arrange for their availability and application to the cost estimating process during the appropriate time phase of the estimating activity.

2.6 Cost Models

Among the many methods for cost estimating, at the design stage, are those based on knowledge bases, features, operations, weight, material, physical relationships and similarity laws. These methods are discussed in the following subsections.

2.6.1 Knowledge –Based Costing

Wei and Egbelu (2000), developed a framework to estimate the lowest product manufacturing cost from its AND/OR tree representation of an alternate process. A major drawback of their framework was that it focused only on processing and material handling costs without considering other direct product costs such as set-up, material, fixtures and labour cost.

Abdalla and Knight (1994a) developed a new methodology that linked a Knowledge-based System (KBS) shell with a solid modelling system and allow the user to create a set of features. The KBS captures topological and geometrical information about the model features and estimates the machining cost for these features at each design stages. The proposed design environment consisted of product design module, cost estimating module, and process planning module. The complete system enabled designers to improve the manufacturing process, reduce production costs and significantly improve the quality of the product. The solid modelling Computer-aided Design (CAD) System, Pro/Engineer was chosen for developing the proposed system. It also contains assembly and manufacturing modules. The developed system provided the following facilities: "(i) direct access to the solid modelling system database for unique and specialised engineering application; (ii) directed access to the database to derive automated feature recognition". A reasoning system was implemented in this research for recognising the feature type (holes, slots, drafts, etc.) by matching the available feature's data with predefined feature characteristics. After creating the component with the solid modelling system, the Feature Recognition System (FRS) defines and extracts the information needed for machining the component's features and sends them back to the process planning system (PPS). Once the PPS receives the necessary information from the FRS, it starts to select the machining data. The system then sequences the selected operations and calculates the machining time, cost. Their approach enabled designers to ensure that the product would be manufactured with existing manufacturing facilities to provide high quality and the lowest cost.

Shehab and Abdalla (2001a) developed an intelligent knowledge-based system for product cost modelling at an early design stage. An earlier version of the developed system has taken into consideration processing and material costs. Further development addressed other essential issues such as non-productive cost and set-up cost (Shehab and Abdalla (2001b)). In addition, a set fuzzy logic models was developed and implemented in the later version of the system to overcome the uncertainty in the cost estimation model.

In a series of papers, Rehman (1997), Rehman and Morris (1996), Rehman and Guenov (1998), a methodology for modelling manufacturing costs at the design phase of a product's life cycle was described. The cost modelling adopted incorporated the use of a knowledge-based expert system approach. Manufacturing cost estimation was automated by linking the design knowledge, required for predicting design features from conceptual descriptions, to the manufacturing knowledge required for process planning. The link between the two paradigms was achieved through the advanced AI architecture, blackboard framework, of problem solving.

The blackboard data structure was responsible for storing the evolving solution and made it visible to the experts. The knowledge sources in the blackboard framework were responsible for moving the state of the blackboard towards a solution state. The various knowledge sources are independent of each other and affect each other indirectly by their contributions to the blackboard. The role of the inference engine is to control the problem solving process. The inference engine monitors the state of the blackboard and when an event occurs, co-ordinated the actions of the knowledge sources.

The role of integration with CAD is to allow the system to analyse the design directly. The data associated with the product design is accessed through a neutral interface file. The role of the link with a relational database is to demonstrate how knowledge outside the system, that is relevant to the cost modelling process, can be accessed by the cost modeller. The prototype expert system is developed in a UNIX operating system environment. This environment includes a complete and powerful graphical user interface, the X Windows system. The prototype is being implemented in the object-oriented programming language of C++.

It is clear, that the above model cannot be used to generate an accurate manufacturing cost estimation. The reason is that this model estimates the manufacturing costs without depending on process planning. But, in order to provide the required manufacturing cost during the design stage, it is necessary to obtain the data required by the manufacturing process from a component model.

Gayretli and Abdalla (1999) presented a prototype constraint-based system for evaluation and optimisation of machining processes. One of the evaluation and optimisation criteria for machining processes was the manufacturing cost. The developed model focused on manufacturing processes optimisation using a combination of mathematical methods, feature-based cost estimation, and constraint-programming techniques. This approach enabled designers to evaluate and optimise feasible manufacturing process of components in a consistent manner as early as possible during the design session.

London et al (1987) developed an expert system architecture that included a cost estimation module and a tutorial module. The main research issue was to customise the expert system to meet an organisation’s needs.

Diplaris and Sfantsikopoulos (2000) presented a new analytical cost-tolerance model that correlated almost all the main items relating to the derivation of the cost of the machining accuracy. The size of toleranced dimensions, the size of its tolerance zone for an intermediate machining operation, the initial dimensional tolerance, and the size of the respective workpiece surface have been considered in this study.

Venkatachalam discussed in a number of papers (Venkatachalam (1994, 1993), and Venkatachalam et al. (1993)) the development process of an object- and rule –based expert system for process selection and cost estimation for casting (including sand, investment, and die casting) and forging (including conventional die, open die, and precision forging) as primary processes. The selection of secondary processes was limited to end milling and drilling operations performed on a CNC milling machine. The set of designs features considered included through holes, blind holes, square holes, and slots.

Luong and Spedding (1995) described the development and implementation of a generic knowledge-based system for process planning and cost estimation in the hole making process. The main function of the system, besides estimating the cost of production, is to recommend appropriate machining parameters in order to meet product specifications. The knowledge required for process planning and cost estimation is organised into three knowledge bases, namely process and sequence knowledge-based, machinability data knowledge-based and costing data knowledge-based. In comparison with the manual system previously used, this system has provided several advantages including the flexibility to change data, and uniform process plans, correct machining parameters, and automatic cost estimation. Another important feature of the system is that it provides a company with a facility to store the knowledge gained by experienced planners in the databases which can then be used to assist inexperienced planners to perform the task of planning and estimating quickly and efficiently. A major feature of this system is that it unifies process sequence, machinability and cost estimation into integrated system, which caters for the requirements of small to medium sized companies involved in batch operations. Luong and Spedding's system lacked a number of desirable features, for instance there was no interface to CAD, and no facility to optimise process plans.

Allen and Swift (1990) developed a technique that could be used in the early stages of the design process for the purposes of manufacturing process selection and costing. The application of the technique as a knowledge-based expert system was investigated and integrated with an automated draughting process. One of the evaluation and optimisation criteria for machining processes is the manufacturing cost.

A knowledge-based (expert) software system, called HKB (from the German 'Herstell-Kosten-Berechnung' – manufacturing cost calculation), that permitted capture of such knowledge, and delivered consistent and reliable calculations of manufacturing costs was developed by Ferreirinha et al (1993). The system can also be used as an aid to manufacturing planning and for producing cost estimates for tendering.

2.6.2 Feature-Based Method

The product or process design has the greatest impact on life cycle cost and quality (Dean and Unal (1991)). A product model can be designed by using features. This is known as design by features or featured-based design. The main advantage of using a feature-based design is that many design features and manufacturing features are similar. Research in feature-based design was reviewed by Salomons et al. (1993). Feature-based design is regarded as an essential factor towards CAD/CAPP integration from a process planning point of view. Feature-based design has the advantage of storing relevant information for applications during the design process, as well as offering the possibility for considering manufacturing and assembly concerns early in the design process.

Ou-Yang and Lin (1997) developed an integrated framework for feature-based early manufacturing cost estimation. Their system tended to estimate the manufacturing cost of a design according to the shapes and precision of its features. The system was consisted of CAD module, reference library module and analysing module. The CAD module supported the feature-based component construction and modification function for the user to perform the design task. The reference module contained manufacturing processes as well as cost related data. The major module of the proposed framework was the analysing module.

In Ou-Yang and Lin’s paper, the major factors, used to estimate the machining time of a feature, were type, process planning information, geometrical data and surface finish requirements. The proposed framework of Ou-Yang and Lin has taken into consideration only conventional machining process. However, machining processes can have limitations in producing certain manufacturing features. For example, the machining process is often not suitable for producing a feature with very small dimensions or very high surface finish requirements. Ou-Yang and Lin's model is suitable for generating manufacturing costs of prismatic components.

Asiedu and Gu (1998) presented a review for the issues of product life cycle cost (LCC) analysis. Tools have been developed to provide engineers with cost information to guide them in design. LCC analysis provided the framework for specifying the estimated total incremental costs of developing, producing, using, and retiring a particular item. Based on the length of the life cycles, products could be grouped into three broad categories. These were large scale, mid scale, and small scale. The distinction between the different types of cycles is important from a life cycle analysis standpoint. They suggested that a framework for life cycle cost analysis could provide designers with the estimated total product cost from development to disposability.

Wierda (1991) developed a feature-based costing system. The approach has many advantages but it was difficult to find reasonable criteria to assign operation costs to design features. In addition, the role of features in design, in design-for-manufacture approaches, in process planning and in cost information tools for designers has been presented.

Accurate cost data is a critical factor for successfully implementing cost estimation system. Sheldon et al. (1993) proposed a framework for developing an intermediate cost database established between the cost accounting system and the design for cost (DFC) system. This system analysed the cost information provided by a cost accounting system to establish the appropriate cost structures suitable for different groups of DFC users.

Das et al (1995) discussed methodologies for reducing set-up costs for machined components. The approach was based on the analysis of machining form features. The basic guidelines for cost estimation in manufacturing can be found in Ostwald (1988).

The group technology (GT)-based cost estimation model is based on the similarity principle. It typically uses a basic cost value while taking into account the effects of variable cost factors such as size and complexity. Among the examples of this model, Geiger and Dilts (1996) developed a conceptual model and working prototype of a new application for blending product design and cost accounting, that of automated design-to-cost. Hundal (1993) described a cost model for predicting costs of products made in different size ranges. The Geiger and Dilts's model integrated the manufacturing and accounting concepts of feature-based modelling, group technology, coding, computer-aided process planning, and activity based costing. The system first calculated the cost of a new component design directly from existing computer-aided design, accounting, and other computer-integrated manufacturing databases. It then found and displayed, along with their costs, all existing components that were similar or 'near' to the proposed component. Geiger and Dilts' conceptual model for an automated DTC system had four main functional components, FBM CAD, group technology classification, nearness searching, and product costing, which were divided into modules of process planning, cost driver quantification, and cost extension.

Based on Manufacturing Engineering Reference Model, Brinke et al (1999) proposed a model for variant-based cost estimation. The Manufacturing Engineering Reference Model distinguished between three types of information structure, namely the Order Information Structure, the Resource Information Structure, and the Product Information Structure. Based on product-characteristics, the similarity between a new product and a previously manufactured one can be calculated for each valued set of comparison criteria. If a new product contained product characteristics, which have not been manufactured before, the required information had to be generated in another way. For instance, a generative cost estimation system can be triggered to calculate a cost estimate for that characteristic.

A generic Cost Estimating tool, applicable to large Made-To-Order (MTO) products, such as ships and power plant, which could be used by designers during the earliest stages in process, was proposed by Buxton and Bull (1996). MTO products are generic in that they usually involve assembling bought-in equipment on to a structure. A generic framework tool for Preliminary Design and Cost Estimating called PRELUDE was developed to extract the relevant data and offered a range of costing methods to calculate comparative costs, displaying the results in ‘real time’ for designers.

Hayes and Sun (1995), developed technologies that enabled the construction of design tools, which automatically generated cost-reducing design suggestions by identifying those areas of the design that are most cost-critical. Identification of those cost-critical areas required an in-depth understanding of how the design would be manufactured. They used a program called the Manufacturing Evaluation Agent to produce cost-reducing design suggestions.

Feng et al. (1996) presented a feature-based manufacturing cost estimation approach. Their system focused on machining form features such as holes, slots flat surfaces, and chamfers. The machining time (cost) of a component depended on the time of performing operations, the changeover and set-up time. In the model, the problem of cost evaluation was formulated to find the shortest path for machining activities such as processes and set-ups. Manufacturing processes for the component were optimised and based on the activity-based approach, in order to reach the optimum solution by assigning unit manufacturing cost to each activity.

The unit manufacturing cost (c_p) of a component for a traditional machining can be calculated as follows:

$$c_p = c_m + c_c + c_s \tag{2. 1}$$

Where:

c_m= the cost of machining l_c unit long workpiece,

c_c = the change-over cost of cutting tools,

c_s =the set-up cost of workpiece

and

$$c_m = \sum_{i=l_{ci}}^{m} c_{ci} \tag{2. 2}$$

Where:

c_{ci} = the machining cost for unit length.

m = the number of machining operations

and

$$c_c = \sum_{j=1}^{n_1} c_j \tag{2. 3}$$

Where:

c_j = the cost of change-over j

n_1 = the total number of change-overs

and

$$c_s = \sum_{k=1}^{n_2} c_{sk} \qquad (2.4)$$

Where:

c_{sk} = the cost of set-up k

n_2 = the total number of set-ups.

Equation (2.1) assumed that the set-up and changeover tasks were performed sequentially. It also assumed that all operations were performed on one machine tool so the transportation, storage, loading and unloading cost were not considered in the equation.

For simultaneous machining operations, the set-up and the changeover costs cannot be calculated separately as expressed in Equation (2.1). Furthermore, the maximum of the set-up and changeover times were used rather than the cost.

$$c_p = c_m + \sum_{j=0}^{n} t_j c_{scj} \qquad (2.5)$$

Where:

c_m is calculated as in equation (2.2)

Multiple machine tools are used when a component cannot be machined on a single machine. In this case, transportation, storage, and loading and unloading costs occur. It is more convenient to use time rather than cost to evaluate designs in this case. Let t_{tj}, t_{sj}, t_{lj}, and t_{uj} denote the transportation, storage, loading and unloading time, respectively, and c_{tj}, c_{sj}, c_{lj}, and c_{uj} are their scaling factors, respectively. Then the manufacturing cost of the component was calculated as follows:

$$c_p = \sum_{i=1}^{m} c_{mi} + \sum_{j=0}^{n} t_j c_{scj} + \sum_{j=0}^{n_1} t_{tj1} c_{tj1} + \sum_{j=0}^{n_2} t_{sj2} c_{sj2} + \sum_{j=0}^{n_3} t_{lj3} c_{lj3} + \sum_{j=0}^{n_4} t_{uj4} u_{uj4} \quad (2.\ 6)$$

Where m and n are the total numbers of machining operations, and set-ups/change-overs, and n_1, n_2, n_3, and n_4 are the total numbers of transportation, storage, loading and unloading activities, respectively.

2.6.3 Cost Models for Injection-Moulded Components

The injection moulding process is the most common moulding process for manufacturing plastic moulded products (Ye et al (2000)). Various cost models, for injection moulding products, have been developed. The basic guidelines for the various elements of the injection moulding operation such as mould design, injection moulding machines, designing products, and plastic moulding material can be found in Rosato and Rosato (1995).

The cost of an injection moulded component is a function of material utilisation, mould design, machine requirements, energy consumption, cycle time, labour charges, and production yields (Kazmer and Speight (1997)).

Mok et al (2001) presented a practical prototype knowledge-based system, called IKMOULD, for mould designing process. In this system, the computational module, the knowledge-based module and the graphic module for generating mould features were integrated within an interactive CAD-based framework. The system was written in UNIX C and implemented on the McDonnell Douglas Unigraphics II CAD system.

Three approaches, for virtual product development of moulds, were described by Britton et al (2000). The first approach was characterised by the use of 3-D computer aided design (CAD) for product design, 2D draughting for mould design and 3-D computer aided design/manufacture (CAD/CAM) for mould manufacture. The second approach was characterised by the use of 3-D CAD models by all three participants. The third approach was a proposed collaborative design process.

Beiter and Ishii (1996) presented a methodology for incorporating component dimensional tolerancing into material selection for engineering thermoplastics. Also, they presented a method for calculating production costs for meeting the component's tolerance requirements. They used the Pressure-Volume-Temperature (PVT) method to estimate shrinkage in thermoplastic components. The impact of best practices in component design, tooling, and standard operating procedures for tight tolerance moulding was described by Kazmer (1997).

Chin and Pun (1994) developed a prototype expert system (ESCOST) for mould cost estimation. The system domain was concerned with the concurrent decision-making of the plastic component design and the mould design, during the cost estimation process. ESCOST made up of seven main components, comprising “Component Design Features and Requirements”, “ material Type”, “Number and Layout of Cavities”, “Injection Mould Design and Features”, “Mould Size Determination”, “Mould Machine” and “Injection Mould Cost Estimation”.

Dewhurst and Boothroyd (1988), described cost models for machining and injection moulding operations. By neglecting non-productive costs, the cost (C_m) of machining a feature in one component on one machine tool was expressed as a sum of machining costs, costs of idle time and a new cutting tool are given by:

$$C_m = M * t_m + Q * (M * t_{ct} + C_t) * t_m / t \qquad (2.\ 7)$$

Where:

M = machine and operator rate

t_m = total machine tool operating time,

Q = fraction of t_m that the tool is cutting,

t = tool life,

t_{ct} = tool changing time, and

C_t = cost of providing new cutting edge.

Under normal rough machining circumstances, a better estimate of machining time would be obtained from the unit power (specific cutting energy) for the material, the volume of material to be removed and the typical power available for machining. Dewhurst and Boothroyd's injection moulding cost model gives the cost C_t of manufacturing N components:

$$C_t = (Nt_i/n_c)(C_r + Cs) + Cn + Cb + NCp \qquad (2.\ 8)$$

Where:

C_r = machine rate,

Cs = machine supervision rate,

Cn = cost of manufacturing cavities in mould base,

t_i = mould cycle time,

Cb = cost of mould base, and

Cp = cost of polymer per component.

This model required only limited information, such as machining time, rate of machines and operators, and types of tooling materials, to estimate the cost of machining. It is clear that the above cost model cannot be used for cost estimation at early concept design stages. The reason is that machining time and tool change time are unlikely to be available and in any event these are only two of the many variables that make up the total cost of a product.

A knowledge-based system for the cost estimation of injection-moulded products was developed by Chin and Wong (1996). The system was based on a decision table technique. It is not a generic system because it has taken into consideration only the manufacture of electrical appliances. Also, Chin and Wong (1999) presented an integrated product concept development and evaluation system for injection moulding components. An expert system toolkit/shell, called KAPPA-PC, was used to develop the proposed system.

Shing (1999) described the procedures for rapidly estimating the approximate manufacturing cost of a moulded component using a computer program, which was developed specifically for this task. This system depended upon the mathematical equations to estimate the manufacturing cost of an injection-moulded component. The estimated cost included the costs of material, mould and processing. A framework and methodology for design cost effectiveness for injection moulding system was developed by Chen and Liu (1999). The effectiveness and usefulness of this system depended upon the completeness and integrity of the knowledge-based. Therefore, in order to use it as a production system for a company, the knowledge-based must be revised and tailored for the specific company.

A computational system for the process design for injection moulding, called CSPD, has been developed by Kwong and Smith (1998). The developed system was based on a black-board-based expert system and a case-based reasoning approach. CSPD was implemented mainly using Prolog as the programming language. It has the capability to: (1) select the injection moulding machine and the mould base, (2) estimate the tooling cost and processing cost.

Another development of software for cost estimation model of injection moulded components was described by McIlhenny et al (1993). In addition to the mould base and process cost, certain factors such as the material cost and maintenance cost were also included in this model. Material selection, processing parameter selection and troubleshooting were considered in the system. This system was designed for use on personal computers.

Chin and Wong (1995) developed an expert system (ESIMCOST) to assist the manufacturers in injection mould cost estimation at the early product design stage. The domain of the ESIMCOST prototype was concerned with the concurrent decision-making of the plastic component design, the injection mould design, and the mould-making process planning during the cost estimation process. An expert system tool/shell, “Personal-Consultant Plus”, was selected to develop the system.

2.6.4 *Cost Estimation Based on Activities*

Activity-based costing (ABC) is a method for accumulating product costs by determining all the cost drivers associated with the activities required to produce the product. An activity based cost analysis model for evaluating the different manufacturing costs, for the multiple feature-based machining methods, was developed by Tseng and Jiang (2000). The activities required for machining a set of features, were analysed using the proposed model. The activities used, in the cost analysis, were tool set-up, fixture set-up and machining tool paths. The activity, related cost for each activity, was analysed based on a consistent time scale. The set of features, which can be machined with the lowest manufacturing cost, was considered a good way to produce the component.

Operation-based cost models were one of the earliest attempts to estimate manufacturing costs. Thus cost models for various kinds of process have been developed. Due to the type of information required, these models can be used effectively only in the final design stage.

A few models were developed to estimate the cost of producing a specific category of products. For instance, research to obtain the cost information for gear drives was carried out by Bruckner and Ehrlenspiel (1993).

Keys et al (1987) discussed electronic manufacturing process system modelling and simulation tools. The manufacturing cost of printed wiring board assembly (PWBA) was the sum of several contributions including material cost, and both variable and fixed costs. The fundamental equation for PWBA unit cost (C) is given as:

$$C = (C_M + C_{MT} + C_A + C_T + C_{TSR} + C_{RM} + C_F) /[\mathrm{Y} + \mathrm{Y}_\mathrm{R}(1 - \mathrm{Y})] + C_{FM} \qquad (2.9)$$

Where the costs are:

C_M = material,

C_{MT} = materials testing,

C_A = assembly,

C_T = PWBA testing,

C_{TSR} = trouble-shoot and repair,

C_{RM} = repair material,

C_F = fixed, and

C_{FM} = field maintenance.

Y and Y_R are the initial test yield and repair yield, respectively.

Ong (1995) presented the development of an activity-based cost estimating system to help designers to estimate the cost of manufacturing a printed circuit board (PCB) assembly at the early concept stage of design. Activities were identified, quantified and the cost allocated based on the amount of activities used by the PCB. A spreadsheet PCB tool was used for the calculation of the manufacturing cost based on the input data, cost build-up table and activity charts. The data required as input included the batch size, life volume, the number of boards per panel, the length of the panel and unskilled and skilled workers' rates. Though the author claimed the model was meant to be used at the conceptual phase of design, the data needed for the evaluation were most probably not be available until the preliminary design stage.

Alexander et al. (1994) developed a cost estimation tool for the designer in the surface mount PCB assembly domain by integrating Computer Aided Design (CAD), Computer Aided Process Planning (CAPP), and cost estimation techniques using a knowledge based framework. The cost module considered tangible factors including the material costs, the equipment costs, process costs, and the labour costs.

Accurate cost data are a critical factor for successfully implementing cost estimation system. A discussion of practices in manufacturing, construction, as well as chemical, electronic, and mechanical industries was given by Sheldon et al. (1991).

Boothroyd and Reynolds (1989) derived a model for the cost of typical rotational components machined from bar in a CNC turret lathe. They found that by using the developed cost model, it was possible to provide information for the product designer who wished to make trade-off decisions regarding the materials and manufacturing methods for proposed components. The role of cost models in design for manufacturing and the requirements for a design for manufacturing cost estimation were reported by Schreve et al (1999). The models presented in this work were on medium-to-light weight mild steel components, i.e. components up to 40 kg and assemblies up to 200 kg.

Kuo (2000) examined a disassembly sequence and cost analysis for electromechanical products during the design stage. The disassembly planning was divided into four stages: geometrical assembly representation, cut-vertex search analysis, disassembly precedence matrix analysis, and disassembly sequences and plan generation. The disassembly cost was categorised into three types: target disassembly, full disassembly, and optimal disassembly.

The aim of function costing is to provide designers with a technique for estimating costs directly from the specification of a product or system (French (1990)). In mechatronic systems and other applications, where systems are made up largely of bought-in components, function-costing seems likely to be a very useful technique for early cost estimation (French (1993)).

Cauchick-Miguel and Coppini (1996) suggested an approach for determining cost per component more precisely. The proposed approach introduced two types of "machine tools contribution factors" based on the workpiece process planning and the machine tool used in a machining process. It was performed under standard cost centre conditions.

Lenug et al (1996) developed an object-oriented system for design and cost estimation for fire protection systems. The aim of the software development was to seek an optimum pipe work design methodology in terms of size, configuration and ease of installation. FORTAN and C++ were chosen to build the system.

2.7 Computer-Aided Process Planning (CAPP)

Process planning, as defined by Chang and Wysk (1985), is the act of preparing detailed operation instructions to transform an engineering design to a final component. The detailed plan contains the route, processes, process parameters, machines, and tools required for production. The process planning functions may involve several or all of the following activities:

- Selection of machining operations.
- Selection of tools.
- Selection of machine tools.
- Grouping of machining operations.
- Determining set-up requirements.
- Sequencing of machining operations.
- Selection of fixturing systems and data.
- Calculations of cutting parameters.
- Generation of tool paths and NC programs.
- Calculation of machining times.

Process planning activity has traditionally been experience-based and has been performed manually. With the evolution of computers, computer-aided process planning (CAPP) systems have been conceived, designed and created in order to help manufacturing engineers to prepare consistent and accurate process plans, thus reducing time and cost and increasing productivity (Kiritsis (1995)). By capturing process planning knowledge within data and knowledge bases, the high demand for skilled planners can be reduced and less skilled planners can be more easily trained, by these systems.

Although, many CAPP systems have been developed, they were not effective enough as far as constraints on machining operations, tolerance, surface finish, feed rate, cost estimation capability, minimisation of manufacturing time and cost, optimum use of available manufacturing facilities, and uncertain nature of the shop floor, were concerned. For these reasons, many companies had their own research groups to develop their own CAPP systems (Marri et al (1998)).

Kiritsis (1995) presented a review of knowledge-based expert systems for process planning and related methods and problems. It is based mainly on literature and partially on a questionnaire carried out by the author.

There are three basic approaches to computer-aided process planning, namely variant, generative, and automatic. The variant approach is a computerised database retrieval approach. It relies on standard plans developed from previously manufactured components (Cay and Chassapis (1997). The generative approach, however, is based on generating a process plan for each component without referring to existing plans. Automated systems eliminate humans from the planning process. The following sections provide a discussion of each of the approaches.

2.7.1 Variant Process Planning

The variant approach was one of the earliest attempts to computerise process planning techniques. In this model, similar components had similar process plans. In order to identify similarities between process plans, computers were used to retrieve, from the system, the plans that match requirements for a specific component. The coding and classification of components were carried out using GT-based coding and a classification model (Leung (1996)).

This process planning approach was good enough to improve upon the existing process planning techniques and was easy to use. However, the limitation of the components to be planned, was a disadvantage, and details of process plans could not be generated. In addition, the disadvantage of this approach is that, the quality of process plan depends on the knowledge background of a process planner.

Recently, some research work has been carried out by using feature-based modelling and artificial neural networks (ANNs) techniques (Devireddy and Ghosh (1999)).

To reduce the manufacturing time of a product, one effective way to develop a machining process plan for a new component, was to retrieve a relevant case of process planning similar to a new desired component and then adapt the retrieved case to meet the new requirements. Chang et al (2000) proposed a mechanism for retrieval of process planning cases. The core of the retrieval mechanism contained: (1) a feature-based representation of a component and cutting processes; (2) indexing of a component; (3) a feature hierarchical structure based on cutting processes; and (4) a similarity metric used to measure the similarity between a new desired component and any old component in the case base. The application domain was for axisymmetric component machining. A prototype based on the retrieval mechanism was implemented on a Sun workstation using the ACIS 3D-Toolkit from Spatial Technology.

2.7.2 Generative Process Planning

This model is defined as a system synthesising a process plan for a new component. Information about the generation of process plans is stored in a manufacturing database. Therefore, details of a plan are available in the database. Using this model, operations required, machine and operation sequences are generated automatically. Other process functions such as machine selection, process optimisation, tool selection are also generated via the generative planning technique. Consistency in process planning is achieved by this approach. In order to execute this approach successfully and effectively, it is necessary to identify the logic of process planning, define the component to be manufactured clearly and precisely in a computer language format, and incorporate the logic of process planning and component description into an integrated manufacturing database. Some popular methods for describing components in this model are codes, special descriptive language, CAD models, and methods for representing logic of process planning are shown as follows:

- Decision trees
- Decision tables

- Artificial intelligence-based approaches
- Knowledge representation

The generative planning approach has the following advantages (Chang et al (1991):

1. It can generate consistent a process plan rapidly.
2. New components can be planned as easily as existent components.
3. It can potentially be interfaced with an automated manufacturing facility to provide detailed and up-to-date control information.

Wu and Zhang (1998) presented a computer-aided process planning (CAPP) framework and its methodology for guiding the design, development and running of the CAPP framework and practical CAPP systems. The methodology of the CAPP framework was divided into three parts, reference architecture, modelling methods, and implementation strategy and method.

Luong and Spedding (1995) developed a generative CAPP knowledge-based (K-B) system. The system was used for process planning and cost estimation in the hole making process. The knowledge required for process planning and cost estimation was organised into three knowledge bases, namely process and sequence knowledge-based, machinability data knowledge-based, and costing data knowledge-based. The feature of the system was that it provided a company with a facility to store the knowledge gained by experienced planners in the databases which can then be used to assist in experienced planners to perform the task of planning and estimating quickly and efficiently.

Gao and Huang (1996) described a framework for modelling and managing engineering product and manufacturing capability information in an integrated feature-based CAD/knowledge-based process planning environment. A feature-based design system is developed with a commercial boundary representation solid modeller incorporating additional feature modelling functions. It is fully integrated with the knowledge-based process planning system through an information mapping mechanism, which processes the design information into the form required by the process planning system. Process planning decisions were made by searching for a match between the product requirements and the process capability of available manufacturing systems. This was achieved by invoking rules in a sequence that has been coded in an inferencing mechanism.

An integrated process planning system, called the Quick Turnaround Cell (QTC), to handle prismatic components with a limited set of features has been developed by Kanumury and Chang (1991). Here process planning could reduce the manufacturing lead-time and provide good process plans. It could also be used during the design stage as a design evaluation tool.

Mamalis et al (1996) reported an approach to the on-line integration of process planning and production scheduling. Based on a geometric modeller, a geometric analyser and a knowledge-based, the process planner generated alternative process plans and provided automatic tool selection and the calculation of the appropriate machining parameters. Time and cost estimations were input to the decision-making module in the production scheduling system that produced optimal scheduling decisions as well as a complete record of the actual state of the factory resources.

A CAPP system was proposed by Jovanoski and Muthsam (1995). Their system consisted of (1) a structure and geometry recognition of the workpiece and (2) an editor for technological data. The main characteristics of a workpiece model, which could be used for process planning, were described. The results of an analysis of workpieces in industry gave an overview of the topological relationships between geometrical elements, which was an essential part of workpiece modelling for future design and planning systems.

Champati et al (1996) addressed the methodology development for achieving one of the important functions in automated process planning namely, automated determination of sequence of machining operations for prismatic components containing various types of form features. They also proposed a framework for using the case-based reasoning approach, to support learning capability in operation sequencing.

Wysk et al (2001) presented an overview of how process plans were used in a shop floor control environment. In addition, the information required from process plans, in order to effectively and predictably control a manufacturing facility, was specified. A generic vision of process planning for control was presented. The result of this vision was a process planning representation scheme that allows process plans to be used as data for a factory control system.

2.7.3 Automatic Process Planning

The third approach is called automatic process planning. It denotes process planning that can generate a complete plan directly from an engineering design model (CAD) data. There is no human decision making process. An automatic process planning system possesses two special features, the first is an automated CAD interface and the second is a complete and intelligent process planner (Chang (1990)). The major difference between an automatic approach and other approaches is the automatic CAD interface capability.

Design for assembly (DFA) is an import part of concurrent engineering strategy for reduction of product manufacturing costs and lead times (Molloy et al (1993)).

2.8 Design for Assembly (DFA)

It is now widely accepted that the majority of the cost involved, in assembly, is determined in the design stage (Appleton and Garside (2000)). Design for assembly is a technique concerned with reducing the assembly cost of a product through simplification of its design. It is an important part of CE strategy for the reduction of product manufacturing costs and lead times. A particular beneficial feature of DFA is that it distinguishes between the design of the product and the design of individual components. It tackles the cost of a product or assembly with special regard to manufacture. Traditionally, DFA has relied on the use of general guidelines and examples to aid the designer (Andreasen et al (1983)). More recently, research work on DFA has concentrated on the evaluation of the ability to assemble in order to facilitate design improvement (Barnes et al (1999)). Wu and O'Grady (1999) developed a concurrent engineering approach to design for assembly using the Petri Nets modelling tool. The concept of combining a single component feature model and an assembly feature model has resulted in an integrated prototype system (Holland and Bronsvoort (2000)).

A number of systems have been developed that enable designers and production engineers to measure the ease or difficulty with which components can be handled and assembled. Assembly cost estimation was one of the criteria used to determine the most economic assembly technique for a product (Daabub and Abdalla, 1999).

Zha et al (1999b) developed an expert system for concurrent product design and assembly planning. This approach is implemented through an agent-based framework with concurrent integration of multiple cooperative knowledge sources and software.

Molly et al. (1993) developed an integrated feature based system in design for assembly environment. The system was designed to perform DFA analysis at the individual component and at the assembly levels. This system was integrated with a CAPP system for the generation of assembly sequences for mechanical components. The system was implemented using C as the programming language, and by using SQL to maintain the databases.

There are two basic approaches for implementing Design for Assembly (DFA), spreadsheet-based and computer-based approaches. The most well known DFA methods will be discussed in the following sub-section.

2.8.1 DFA Techniques

The Assemblability Evaluation Method (AEM) by Hitachi examines each component in the sequence of the assembly process and determines the necessary operations for assembling the component (Miyakawa et al (1990)). There is a corresponding numeric value for each operation, which tries to quantify the difficulty or ease of this operation. These values are filled in predefined forms and the resulting total, for the whole product, was used as a measurement of its ability to be assembled. A computer system supports the calculation of the results. Products or individual components with a poor assessment can then be redesigned using a catalogue of rules and domain- specific examples. The method was easy to learn, fast to perform, and the results obtained related to insertion and fastening of components are remarkably precise. It is suitable for typical mass production products like tape recorders or vacuum cleaners. The shortcomings of this method were that the costs for component handling and orienting were not considered and that the estimation of the actual assembly costs was uncertain.

DFA was initiated at the University of Massachusetts (USA) by Boothroyd and Dewhurst (1983). Basically, Boothroyd's DFA evaluation technique was performed by worksheet approach. Firstly, one had to examine which components are necessary to the function of the product, and the ones which could be eliminated. This was carried out based on three evaluation criteria:

- ♦ During operation of the product, does the component move relative to all other components already assembled?
- ♦ Must the component, be produced from a different material or be isolated, from all other components already assembled?
- ♦ Must the component be separate from all other components already assembled because otherwise necessary assembly or disassembly of other separate components would be impossible?

If the answer to any of these questions is yes then the component is essential for the product. Inputs for the DFA evaluation technique were, product engineering drawing, exploded 3-D views and assembly sequence. Then the outputs were the assembly time and cost for component handling and inserting together with valuable information on suggestions for redesign. A drawback of this method was that the product analysis was both complicated and time consuming.

The Lucas DFA methodology (Lucas (1992)) has been proven to improve the overall manufacturability and assemblability of products and thus reduce costs. It recognised the definition of an assembly sequence, the analysis of each component and the ease of handling and fitting. This resulted in handling and fitting indices being generated. It also took into account the availability of gripping surfaces.

The above DFA methods were carried out on a completed product design. At that stage of design any redesign is very expensive and the lead-time of the product is increased. These techniques relied upon spreadsheets and set questions to be answered regarding the functionality and the various components of the product.

Much effort has been done on the development of DFA expert systems (Daabub & Abdalla (1999); Strobl & Dodenhoft (1992), Goodman et. al. (1991)). In general, these systems consisted of a design tool (CAD), a knowledge-acquisition and storage tool and an inference engine. Waterbury (1986) discussed the implementation of the DFA principles in which he noted that DFA requires more than simply applying a few principles and entailed subjective evaluations and human adjustment.

There are three basic assembly techniques, manual, automatic, and robotic. In practice, assembly systems can be a combination of one or more of these methods. Each of these techniques has its appropriate range of conditions for economic application, depending on the number of components to be assembled, the production volume, etc. It is important to decide at an early design stage, which type of assembly method is likely to be adopted, based on the method yielding the lowest costs (Boothroyd & Dewhurst (1987)). The reason, that early process selection is important, is that manual assembly differs widely from automatic assembly in the requirements it imposes on the product design. An operation that is easy for an individual person may be very difficult for a robot or special -purpose work-head, and conversely it may be difficult to carry out operations that are easy for machines but difficult for people. The following subsection will review the previous work in the area of design for robotic assembly.

2.8.2 Design for Robotic Assembly

Since their first introduction in the early 1960s, industrial robots have made significant inroads into many applications areas. They have been welding car bodies and other assemblies in the automotive industry, painting the interior of car bodies, and assembling car engines and cylinder heads, for over 20 years (Wilson (1999), Leikas (1999), Kimmelmann and Wolbring (2000), and Grohmann (1996)). Also, robots can be used to disassemble explosive components, which would present a hazard to humans taking them apart (Ray (1996)). The general design criteria for design for robotic assembly can be found in (Boothroyd (1992)).

Technical and economic reasons are the primary reasons for using robots for assembly tasks. Social issues are a secondary incentive, and all these three items have a financial dimension. Objectively, manual and robotic assembly systems can be compared by using five parameters as shown in Table (2.1), capital cost, output, quality, reliability and cost per unit (Owen **(**1985).

Comparing Parameter	**Manual Assembly**	**Robotic Assembly**
Capital cost	Low	High
Output	Unpredictable	Predictable
Quality	Variable	Consistent
Reliability	Unreliable	Reliable
Cost per unit	Constant	Decreasing

Table (2.1) Comparison between Manual and Robotic Assembly Systems

It would appear that, from the economic viewpoint for the assembly processes, the main distinguishing features of a robot are that it can be programmed to perform a cycle of several different operations quickly and can be engineered easily to adapt to changes in product design or style variations.

Although robots are an important part of the total investment, in robotic assembly the major expenditure is almost invariably on peripheral equipment such as grippers, feeders, tooling and fixtures. The gripper is the mechanical interface between the robot and its environment. Without it the robot cannot perform the pick-and-place functions needed for assembly tasks. Therefore, efforts were spent on trying to reduce the cost of peripherals (Pham and Yeo (1991). Guidelines for designing grippers for use in a modular manufacturing work cell have been developed by Causey and Quinn (1998). The guidelines have been divided into two main categories, those that help improve the throughput and those that increase the reliability. Baartman and Storm (1994) built a generic industrial gripper that is as fast as a normal gripper, and is able to grasp more component shapes more stability. Programming of the gripper is partly automated, to provide flexibility to the design process.

Offodile et al (1991) presented a knowledge-based model for selecting robotic systems for mechanical assembly. The knowledge based system tool was used to select a robot from available robotic systems using cost and performance criteria along with the parameters for the assembly cell. A computer program was written to store information on available robotic systems in a knowledge-based. The information was accessible in an interactive mode using the knowledge of the assembly task.

The following sections will address the product cost modelling with emerging AI techniques including fuzzy logic, neural networks (NN), and genetic algorithms (GAs).

2.9 Fuzzy Logic

Fuzzy logic has been used as the basis for controlling industrial processes and consumer products since it was invented by Zadeh (1960). By applying the fuzzy concept, it is possible to handle the uncertainty in cost estimation problems due to implementing subjective concepts and imprecise information. Several recent papers have suggested that fuzzy logic along with other techniques, in the area of soft computing, may be useful for cost estimating purposes (Mason and Levy (1996)).

Shehab and Abdalla (2001d) proposed a set of fuzzy logic models to overcome the uncertainty in the cost estimation model. The input cost drivers of the developed fuzzy logic model were component volume, shape complexity and surface finish. While the output variable was the machining time. In the model, with three independent variables, each of which consists of a number of membership functions, a (3 x 3 x 5) decision table with forty-five rules were constructed.

El Baradie (1997) developed a fuzzy logic model for machining data selection. The model was based on the relationship between the hardness of a given material and the recommended cutting speed. The objective of the model was to facilitate the computerisation process of the vast body of machining information contained in machining data handbooks. In addition, the proposed model suggested the possibility of developing an expert system for machining data selection based on fuzzy logic.

A fuzzy logic expert system, for estimating excavation costs, was developed by Mason et al (1997). The input independent variables were the depth of ground water and political stability and the output variable was the excavation cost. A rule-based fuzzy approach for considering uncertain items in cost estimation at flat plate processes (FPP) presented by Jahan-Shahi et al (1999). The input variables in this model were plate thickness, plate size, and labour skill level and the output variable was plate carrying and loading time.

An algorithm for solution of the stochastic geometry program, that could be used to find an exact cost of the product in uncertain industrial environment, was developed by Jha (1992). This methodology focused on estimating the probable cost range and by calculating the expected cost. In addition, it estimated the cost of some manufacturing processes such as hole making process by injection moulding.

Ping et al (1996) developed a multi-agent system for cost estimation. They stressed that the existing cost estimation methods presented two problems:

- They were incapable of specifying a cost estimation process for complex components, and
- They did not give any idea of the uncertainty at an early stage of the design process.

In this system, each agent represented a kind of cost estimation method. The system used a fuzzy classification of cost estimation methods. It included a dynamic optimisation structure to provide the agent with knowledge from the past. The system classified user requirements, made the expert agents execute the design tasks. The model was based on an integrative system blackboard system. It used a combination of these two paradigms to reduce communication cost, and minimised the disadvantages in information exchange bottleneck between agents.

Edwards and Petley (1993, 1995) introduced capital cost estimation by applying fuzzy matching. A practical guide to the design techniques was used to establish fuzzy controller and was presented by Kouatli and Jones (1990). An example of the use a welding robot to obtain an irregular weld path profile was used to illustrate the procedure. A general overview of the development of fuzzy logic has been given by El Baradie (1998). He presented a number of the industrial applications where the fuzzy logic approach was used to design consumer appliances.

Hashmi et al (1999) applied fuzzy logic principles for selecting cutting conditions in machining operations. In this model, the fuzzy-metric arcs were overlapped at 50%. The material data, used for theoretical calculations, were for medium-carbon leaded steel (BHN 125-425) and free-machining carbon wrought steel (BHN 225-425). Wong et al (1999) developed a fuzzy logic based system for selecting the metal cutting data.

2.10 Neural Networks (NN)

A Neural Network (NN), sometimes called Artificial Neural Network (ANN), is a novel form of Artificial Intelligence (AI) which empowers computers to handle intuitive types of problems, that require the integration of experience from often seemingly unrelated sources, and make decisions that cannot be clearly defined in mathematical terms (Fung and Popplewell (1994)). The human brain is very good at this type of computing. A neural network attempts to simulate the structure of the human brain and the method in which a human processes data. In engineering, fields, one of the most important applications of ANN is modelling a system with an unknown input-output relation.

Neural networks (NN) have recently been used in modelling of cost estimation. Creese and Li (1995) applied NN to the cost estimation of timber bridges. McKim (1993) presented an NN costing model for multi-stage horizontal pumps. The major limitation of NN approach was that due to its black-box characteristic it was not possible to explain the obtained results.

A feature-based product cost estimation approach, using back-propagation neural networks, was published by Zhang et al (1996). A computer based system for cost estimation of packaging products was developed using the proposed approach.

Smith and Mason (1997) examined the performance, stability and ease of cost estimation modeling using regression versus neural networks to develop cost estimating relationships (CERs). Results showed that neural networks had advantages when dealing with data that did not adhere to the generally chosen low order polynomial forms, or data for which there was little *a priori* knowledge of the appropriate CER to select for regression modeling.

The development of NN models, for estimating costs of drilling operations, was presented by Wang et al (2000). The essential structure of the neural network developed, was made up of three basic types of layers, i.e. input, hidden and output.

A computer aided process planner for metal furniture assembly, welding and painting using a rule based expert system integrated with an artificial neural network was presented by Wilhelm et al (1995). The if/then rules created components lists and process plans, while the neural network estimated the standard processing times for individual product variations.

2.11 <u>Genetic Algorithms (GAs)</u>

2.11.1 Genetic Algorithms Fundamentals

Genetic Algorithms (GAs) are optimisation methods that adopt search strategies that imitate the mechanisms of natural selection (Senin e al (2000)). GAs derive their name from the fact that they are loosely based models of genetic change population of individuals. As biological individuals, whose characteristics are encoded in their genetic material, GAs encode the contents of each candidate solution for a mathematical optimisation problem into the genome of a hypothetical individual. Individuals compete for survival by gaining a higher probability of reproduction, which depends upon their fitness score (i.e. the objective score of the candidate solution they represent). Mating mechanisms based on crossover and mutation manipulate the genomes of the parents to produce offspring that then form a new generation of solutions. Over several generations the genetic characteristics of the population improve until optimal solutions arise.

The genetic algorithms method differs from other optimisation and search methods in that it works with a coding of the design variables not the variables themselves. It searches from a population of points in the design space not from a few points. It uses objective function information, not derivatives or other knowledge, and it uses probabilistic transition rules for selection of a potential solution. GAs are not influenced by the search start point, or by the continuity of the search space, or assumptions about convexity. Since they are highly parallel, they are well suited to combinatorial problems. Since crossover and mutation are controlled by probabilistic parameters, the GAs are to be considered as stochastic search methods.

2.11.2 Applications of GAs-Based Approaches for Manufacturing

Senin at al (2000) investigated the application of genetic algorithm (GA)-based search techniques to concurrent assembly planning, where product design and assembly process planning are performed in parallel, and the evaluation of a design configuration was influenced by the performance of its related assembly process. They found that GAs seem a suitable choice for those planning applications where response time was an important factor.

A method for tolerance synthesis of machining components was introduced by Shuping et al (2000). The method consisted of three steps. Firstly machined components were evaluated using second-order fuzzy comprehensive evaluation. Then a mathematical model for tolerance allocation was formed based on the machinability of the components. Finally, the model was solved using a genetic algorithm.

The allocation of design and machining tolerances had a significant effect on both manufacturing cost and quality. Al-Ansary and Deiab (1997) presented a procedure to concurrently allocate both design and machining tolerances based on optimum total machining cost. The non-linear multi variable optimisation problem formulated was solved using the genetic algorithms method.

Kanai et al (1995) developed a computer aided method for 3-D tolerance synthesis. The assembly was represented by solid model, and dimensional and geometrical tolerances were formulated as a set of inequalities constraining substitute features. The cost database described the relation among the type of features, tolerance ranges, machining and set-up costs. Tolerance synthesis was presented as the combinational optimisation problem under the stack-up conditions. A genetic algorithm (GA) was applied to solve the problem.

2.12 Summary of the Previous Research Work

This chapter presented a critical analysis of previous research work in major areas related to this research in details. In the literature review, in the area of the product development process it was pointed that the product development process plays an important role to develop a successful product cost modelling system. Chin and Wong (1999) stressed that there were two common problems in product concept development and evaluation namely, inadequate exploration of all feasible alternative concepts and ineffective integration of product design concepts with evaluation criteria such as ease of manufacturing and product costs.

In the area of Concurrent Engineering it was pointed out that the CE approach requires the early considerations and involvement of various activities associated with the product development process in simultaneous rather than sequential. Despite the presence of many tools, techniques, and methodologies developed for supporting CE, to achieve the above aims, the potential of CE has not yet been fully exploited.

In the areas of feature-based systems for process selection and evaluation, previous research work has focused on form features, which are the key to selection and evaluation of manufacturing processes. A number of process plans were assigned to the component, and each plan was evaluated by using some criteria.

A review in the area of the product cost modelling with emerging AI techniques including fuzzy logic, neural networks (NN), and genetic algorithms (GAs) was carried out. Most of the existing systems for product cost modelling lacked of the use these techniques.

Marri et al (1998) emphasised that most of the exiting CAPP systems have limited functions for time/cost estimation capability. It was also suggested that a CAPP system had to offer an integrated facility for process planning and time/cost estimation in order to help medium sized companies.

Wierda (1990) emphasised that designers need two types of cost information. Qualitative cost information was needed to support the choices that designers had to make and guides them on their way to a cost-effective design. In contrast, quantitative information specified costs and/or savings for the current design. It enabled designers to check their designs against target costs.

Asiedu and Gu (1998) stressed that there is a need to develop a model and a framework that considers all aspects of the product life cycle. This model should be able to offer engineers information that can readily provide estimates with minimal inputs, include the treatment of uncertainties, identify cost drivers and offer optimal design solutions.

A literature review, in the area of manufacturing cost estimation, showed that a number of cost models have been developed for various kinds of applications. However, very little effort was made in cost modelling at early stage of the entire product development cycle. The major limitations of these systems were that:

- Most of them were mainframe based, quite expensive, and required a long learning curve,
- They lacked the material selection capability,
- All aspects of the product life cycle such as the assembly stage were not considered in these systems,
- There was no system that unified the product cost modelling and DFA in one integrated system.

To summarise, the previous systems were applied on completed product designs. At that stage of design the necessary redesigning is very expensive and the lead-time of the product is increased. These techniques relied on spreadsheets and set questions for the designers to answer regarding the functionality and the various components of the product. So far little research work has been carried out for the product re-design suggestions for ease robotic assembly operation.

2.13 Scope of the Present Work

It has been recognised that, reducing the cost of a product at the design stage is more effective than at the manufacturing stage. Therefore, if the product manufacturing cost can be estimated during the design stage, designers can modify a design to achieve proper performance as well as a reasonable cost at this stage.

To overcome the shortcomings described in the previous section, an integrated framework PC-based system for product cost modelling to achieve several objectives is proposed. Firstly, a methodology for modelling manufacturing costs during an early design stage is developed. Secondly, the proposed system accomplishes an environment that assists inexperienced users to estimate the manufacturing cost of a product. Thirdly, the system will select the most economic assembly technique for a product. Finally, the system advises users how to eliminate design and manufacturing related conflicts that may arise during the product development cycle.

To achieve the aims and the objectives of this research work, which have been set out in section 1.5, several major steps are proposed:

- Developing a methodology for modelling product costs at early design stage,
- Constructing a knowledge-based system (KBS) for cost modelling,
- Applying a set of fuzzy logic models to deal with uncertainty in the knowledge of cost model in order to generate reliable cost estimation,
- Integrating the KBS with both material selection database and a CAD system.

CHAPTER 3

3 THE PROPOSED PRODUCT COST MODELLING APPROACH

3.1 Overview

The purpose of this research work was to develop an intelligent knowledge-based system for product cost modelling and design analysis for automation at early design stage of the product development cycle. Two manufacturing processes, namely machining and injection moulding processes were taken into consideration in this research. Selection of the most economic assembly technique for the product, was taken into consideration as essential element of cost modelling. Additionally, design analysis for automation and design improvement suggestions to simplify the assembly operations are provided. The application of the proposed model is discussed later in this thesis.

The system also has the capability, besides estimating the cost of a product, to recommend appropriate machining processes, their sequence and machining parameters in order to meet product specifications. These recommendations are based on the manufacturing resources and capabilities that the user provides to the system. The manufacturing costs of the product are estimated, based on the recommended process plan. In addition, the system provides recommendations when a design cannot be manufactured within the available manufacturing resources.

This chapter describes the developed methodology for product cost modelling. The knowledge-based approach to cost modelling and the various options of the developed system are presented in Section 3.3. Section 3.4 is devoted to explaining the details of the overall architecture of developed system. Finally, the system scenario and implementation have been explained in Section 3.5.

3.2 Introduction

Product design plays an important role in determining the cost and quality and thus the effective life of a product. In conventional manufacturing organisations, the activities involved namely, market analysis, product design, production system design, manufacturing, and sales, take place in sequential order. This creates "mental walls" between the departments that hinder the flow of information. Hence cost and manufacturing information do not always arrive in the design department when it should. As a result, designers have insufficient knowledge of production, purchase and costs to enable them to make cost-effective and production-oriented decisions (Wierda (1990)).

Concurrent engineering is one of the key concepts that enable companies to improve product competitiveness by incorporating product life cycle values into the early stages of design. These values relate to the entire product life cycle from conceptual design through manufacturing to disposal, including product functionality, cost, manufacturability, assemblability, serviceability, and even recycleability (Prasad (1996), Jo et al (1993)).

Product designers are mainly concerned about their products' performance and functionality and rarely take manufacturing and cost effectiveness constraints into consideration at the design stage. Design for cost effectiveness is concerned with the factors that affect the cost of a component, such as material cost, tooling cost, manufacturing method, cost of tolerance and surface finishes for selected manufacturing method. This required a highly skilled and experienced designer. It can be seen as a process consisting of a series of tasks that transforms a non-economically producible component geometry into an economically producible one. To fully analyse and model such a complex activity, modelling techniques are required (Chen and Liu (1999)).

Design-To-Cost is the use of cost as a design parameter. It has long been evident, though rarely put into practice, that design and manufacturing are interrelated activities and that efficient, cost-effective production can be achieved when product designers consider the manufacturing equipment to be used, and vice versa (Alexander et al

(1994)). Selecting the most appropriate manufacturing process in terms of technological feasibility and cost, for a component design, is one of the most important decision-making tasks. Failure to get it right normally results in components that are of variable quality and/or expensive to make.

Cost estimation plays an important role in the product development cycle. For instance, a proper cost estimation can help designers make good trade-off decisions regarding product structures, material, and manufacturing processes. Therefore, the product cost must be identified at early stage of design process where a large portion of the manufacturing cost is determined.

3.3 Knowledge-Based Cost Modelling System

The increasing significance and enormous potential of a knowledge-based system (KBS) for industry and the ways it can improve decision-making have long been recognised. A knowledge-based approach means developing a system usually called a knowledge-based system (KBS), for making decisions, or as support in decision-making. A KBS in the form of either a computer program or a narrative procedure description should contain structured knowledge of a field of expertise. KBS provides a methodology for solving ill-structured problems that are difficult to handle by pure algorithmic methods. It acquires knowledge from human experts and applies it to solve real problems by reasoning and decision-making. The major advantage of the expert system over a conventional software system is the explicit representation and manipulation of a body of knowledge.

A knowledge-based approach has been developed for product cost estimation through the entire product life cycle. The proposed system has several main options, design for assembly, cost modelling for machining processes, and cost modelling for injection moulding process. The system is designed to provide users with the option of either running the entire integrated system or operating the individual modules separately.

The assembly cost of a product is often significant, and hence must be included in the manufacturing cost estimation (direct material and direct labour). Past studies have shown that the proportion of assembly cost could be as high as 50% of the total manufacturing cost (Venkatachalam et al (1993)) in many mechanical and electrical assemblies. The proposed system enables designers to estimate the total product cost including the assembly cost. The assembly cost estimation is based on the most economic assembly technique that the system suggests to the user. The proposed system has the capability to estimate the assembly time and cost for manual, automatic, and robotic assembly methods. Also, the system provides the design analysis for automation and design improvement suggestions for a product.

It is usually not sufficient for designers to give an estimate of costs of the component or product as a whole. A designer would also like to know why costs are too high and how they can lower them. In other words, the designers would like to see the relationship between costs and aspects of the design that he/she can influence directly. A potential solution is to try to specify costs per design feature. In ideal circumstances this would lead to a situation where costs for the component, as a whole, are the sum of the costs of the individual features. Therefore, the system is designed to generate feature-by-feature (sometimes called feature-based cost) cost estimation report in order to highlight the features of high manufacturing cost. The cost estimation report can be saved as well as printed out for the user.

3.4 <u>The Overall Architecture of the Proposed System</u>

A knowledge-based approach has been developed for product cost estimation through the entire product life cycle. The proposed system comprises of a CAD (computer aided design) solid modelling system, a material selection module, knowledge-based system, process optimisation module, databases, design for assembly module, cost estimation technique module, and user interface. The system is integrated with a material selection software, to facilitate the material selection process. The overall structure of the proposed system is shown in Figure (3.1). Two manufacturing processes were considered in the proposed system. These processes are the machining processes and the

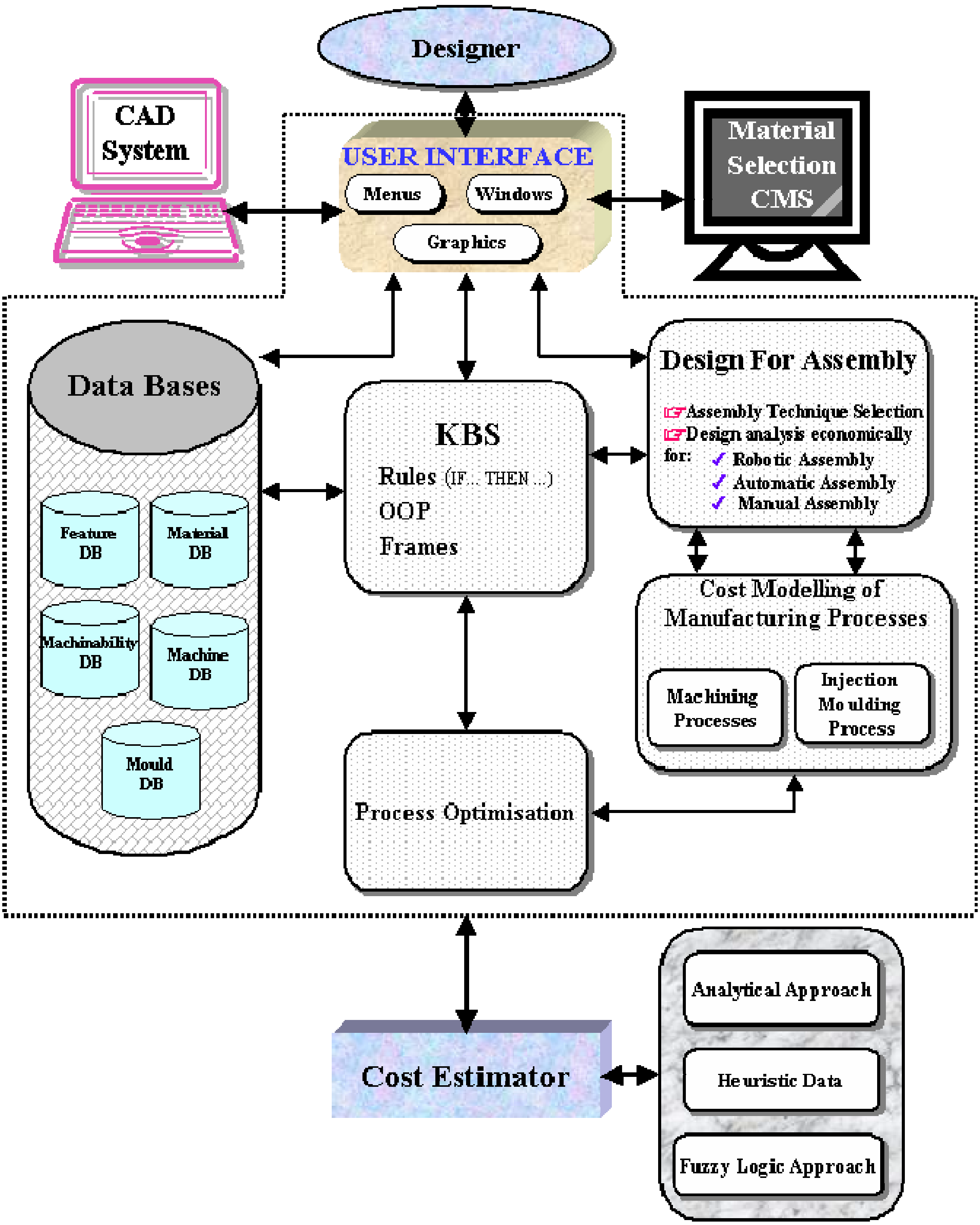


Figure (3.1) The Overall Structure of the Proposed System injection moulding process. The users can run the entire integrated system or operate the individual modules separately.

The prototype system is developed with the attributes of well-engineered software system, such as maintainability, reliability, and efficiently in mind. An expert system, KAPPA-PC™ (1993) toolkit developed by Intellicorp, together with the CAD system (AutoCAD™) and the Cambridge Material Selector (CMS), were seen as an ideal medium for achieving the goals of this research. Consequently, the integration between the reasoning system, the material selector and the solid modeller was considered as an essential task for achieving the objectives of this project. The power of KAPPA-PC lies in its support for rule- and objected-based knowledge representation schemes. The rules of Kappa-PC have been implemented for process selection and cost estimation heuristics. It also provides a programming environment and integrated set of tools to build knowledge-based system for commercial and industrial applications. It allows writing applications in a high level graphical environment and generates standard ANSI C code and GUI runtime. The rules of Kappa-PC have been implemented for process selection and cost estimation heuristics. The reason for selecting AutoCAD as CAD tool is that it is widely used and has powerful interactive functions in editing graphics and drawings. The system runs on personal computers (PC) and is designed to minimise the number of manual keyboard inputs wherever possible, as it is menu driven. Relational databases are used to produce a generic cost estimation system.

The tangible benefit of implementing this system is that the product manufacturing cost can be estimated at the early stage of the product development cycle. Therefore, a quicker response to customers' expectations is generated. Also, it accomplishes an environment that assists inexperienced users to estimate the manufacturing cost of a product. One of the advantage features of this system is that it warns users of features that are costly and difficult to manufacture. In addition, users can modify the product design at any stage to achieve the targeted cost.

Design for assembly (DFA) is an important part of the concurrent engineering strategy for reduction of product manufacturing costs and lead times (Molloy et al (1993)). It is now widely accepted that the majority of the cost involved in assembly is determined in the design stage (Appleton and Garside (2000)). Design for assembly is a technique concerned with reducing the assembly cost of a product through simplification of its design. The proposed system enables designers to estimate the total product cost including the assembly cost. The assembly cost estimation is based on the most economic assembly technique that the system suggests to the user. In addition, the system provides the design analysis economically for manual, automatic, and robotic assembly techniques and design improvement suggestions for a product. The various components of the proposed system will be discussed in details in the following sections.

3.4.1 Material Selection

The most important factor in the total cost of a manufactured component is the cost of the original work material. This direct material cost frequently forms more than 50% of the total cost (Boothroyd et al (1994)), and therefore, should be estimated with reasonable care. The performance of an engineering component is limited by the properties of the material of which it is made, and by the shapes to which this material can be formed (Ashby (1999)). Therefore, material selection is an important stage and complicated one that is made early in the design process.

Material selection is an activity normally performed by design and material engineers. There are many constraints for material selection, such as product functionality, material cost, and the type of manufacturing process. In order to select a material, the system prompts the user to choose between two options for the material selection. These two options are illustrated in Figure (3.2). The first option is that the user select to specify the material based on his/her own criteria. The second one is that the system executes Cambridge Materials Selector (CMS) software (1994). CMS is a computer package consisting of a database, a management system, and a graphical user interface. The database contains quantitative and qualitative data for a wide range of engineering material: metals, polymers, ceramics, composites and natural materials. The management system provides an interactive graphical selection environment suitable for mechanical engineering design. With CMS, the most appropriate material will be determined based on previous input of product concepts and requirements. An example of a materials selection chart, which is generated by CMS, is shown in Figure (3.3). A material can be selected satisfactorily by specifying ranges for the previous selected material properties.

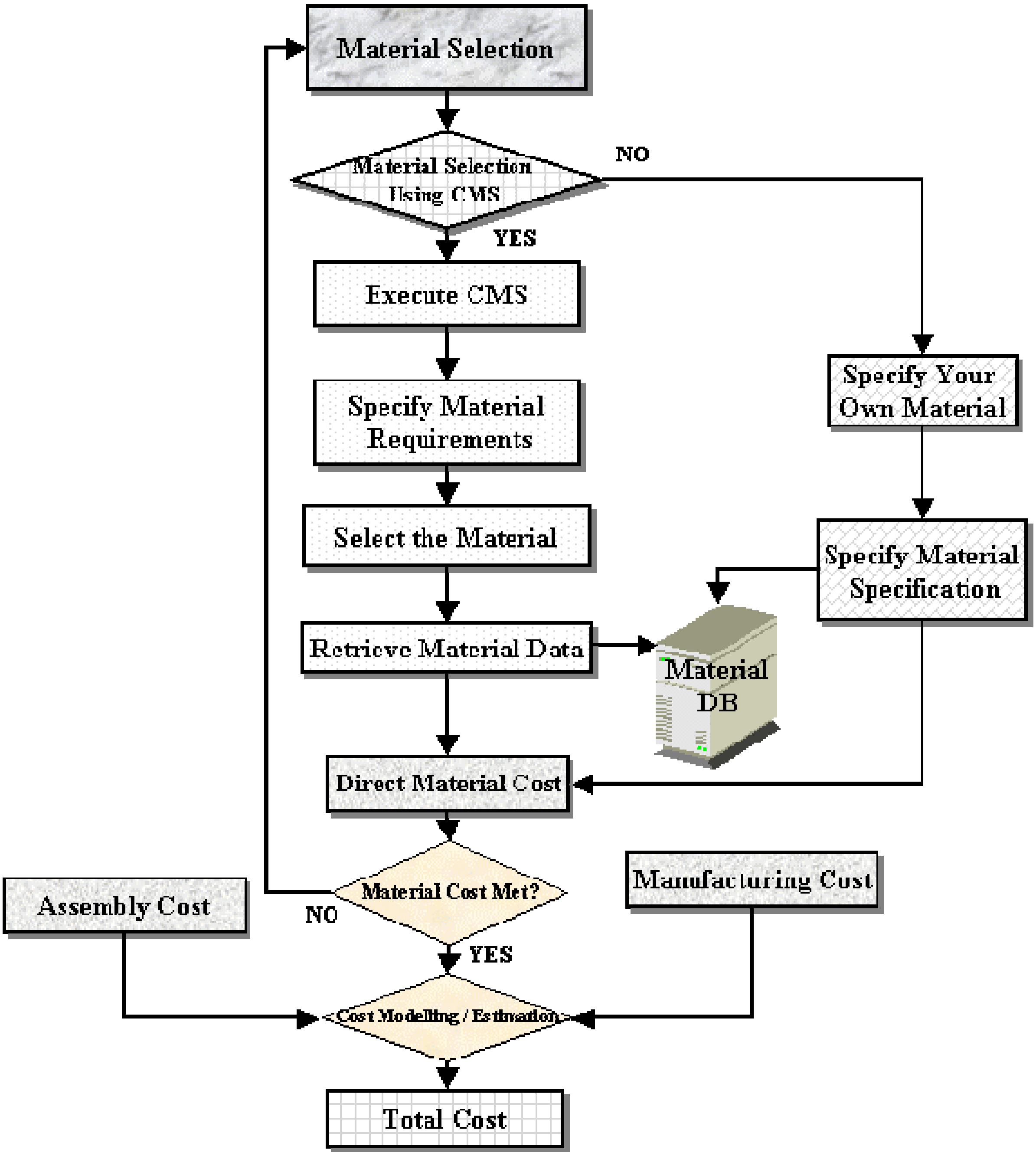


Figure (3.2) Material Selection Flowchart

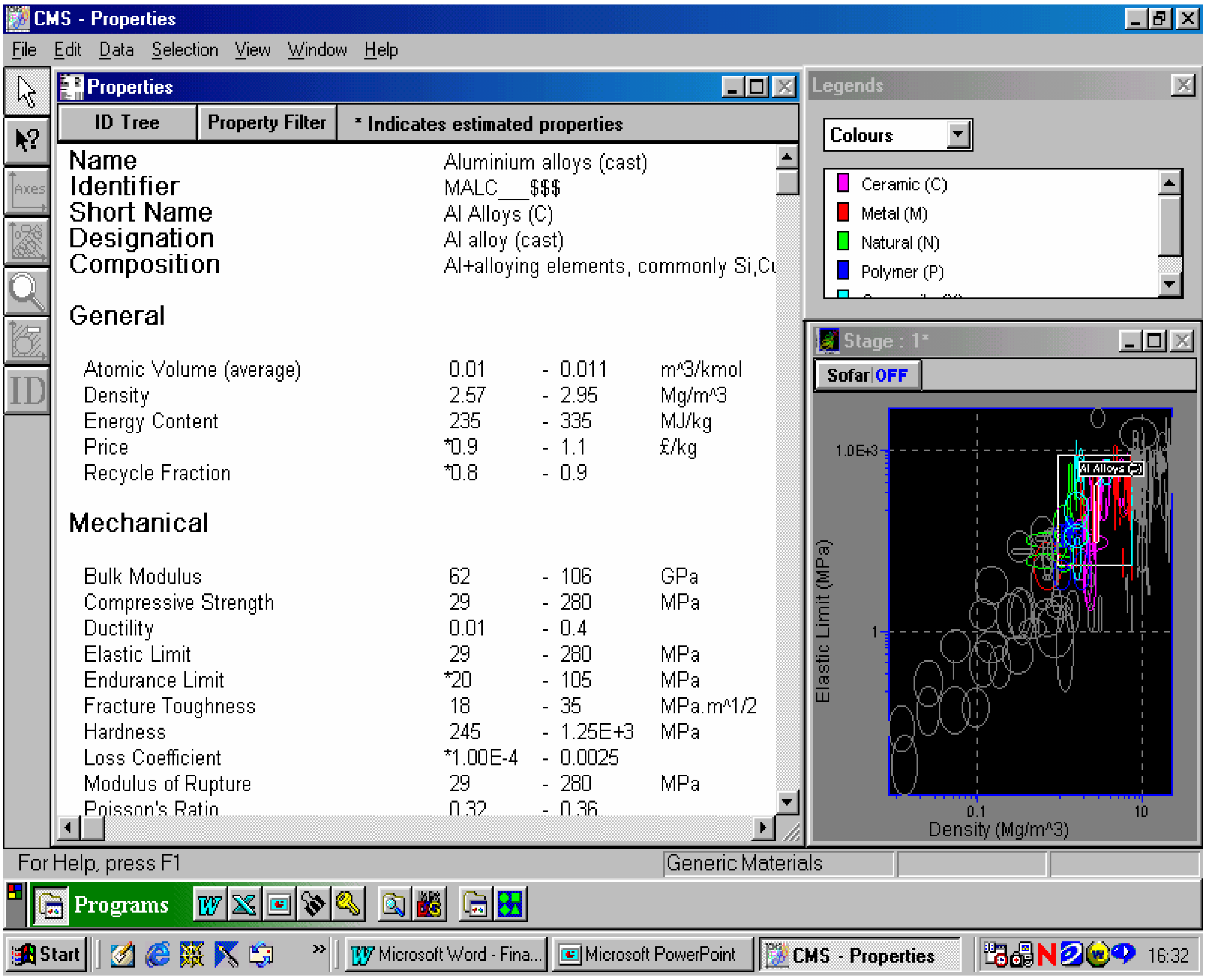


Figure (3.3) Material Selection Chart and Material Properties within CMS (version 2)

The properties of the candidate material are stored as a data file. Hence, the proposed system retrieves all the data necessary to estimate the material cost for a specific component and the machining cutting conditions. The material database is used to store the data about the selected material such as specification and unit cost of the material.

3.4.2 Databases

A database is a group of cross-referenced data files. These contain all the necessary information for an application. There are four approaches to construct a database, namely the hierarchical, the network, the object-oriented and the relational approach.

The proposed system was developed using the relational database approach which in turn comprised of permanent (static) and temporary (dynamic) databases. The permanent database, which includes machine tools and machinability, is not altered as a result of using the system over a period of time. On the other hand, the temporary database, which includes feature specification database, is updated as a result of running the system.

The databases in the system consist of five separate groups of database, feature database, Material database, Machinability database, Machine database, and Mould database. The feature specification database is used to save data on the individual features of a component, such as the volume and various parameters used to define each feature. The parameter type is varied according to the different kinds of features. The feature defined parameters include its identification number (ID), name, geometrical parameters such as its dimensions and location, and technological parameters include the dimension tolerance and surface finish of the feature. The machining specification database stores related data on the available machines and the kind of operations, that can be performed by each machine, the surface finish and tolerance ranges for individual machines, and the operating cost for each machine. The machinability database contains information on machinability of the work material, Brinell hardness, recommended cutting speed and feed rate. The material database is used to store the data about the selected material such as specification and unit cost of the material. Finally, the mould database contains the number of the base plates, number of cavities, wall thickness, the component envelope dimensions and volume, and the mould base cost.

3.4.3 Knowledge Bases

Knowledge representation is the formal description of the knowledge with symbolic encoding. It deals with how to organise and encode knowledge in the best form so that problems can easily be solved. Many representation techniques, such as production rules, object orientation, semantic network and framework have been reported in AI, to meet the requirements for specific problems. Hybrid knowledge representation techniques, such as production rules, frames and object oriented are employed to represent the various knowledge-based systems (KBS) in the developed system. The

KBS were written in a modular structure, namely: Machining Processes, Injection Moulding Process, and Design for Assembly. More than eight hundred rules have been established in this research. The rules, which have been formulated and used in the system, link objects or instances and have the following format:

IF <*antecedent*$_{(1)}$> <*antecedent*$_{(n)}$>

THEN <*consequent*$_{(1)}$> <*consequent*$_{(m)}$>

The antecedent typically contains several clauses linked by the logical connectives **(AND)** and **(OR)**. The consequence consists of one more phrase that specifies the action to be taken.

3.4.4 User Interface

The user interface plays an important role in the ease of operation of the system. It is the section of the system with which a user comes into contact, and which he/she forms an initial impression. The user interface must allow the designer to work quickly, easily and with as little familiarisation as possible. The application interface is very user-friendly and enables easy access to the system, even for a new user. The user communicates with the system using a mouse, a menu, keyboard and display screen. The display screen includes several distinct windows, each displaying either information from a knowledge-based or user input options. An example of this is shown in Figure (3.4).

3.4.5 Cost Estimation Techniques

A combination of heuristics data, algorithmic approach, and fuzzy logic techniques were implemented. The developed system allows users to generate accurate cost estimates for new designs and explore alternative materials and process. Further details of the various cost estimation techniques are explained in chapter 4.

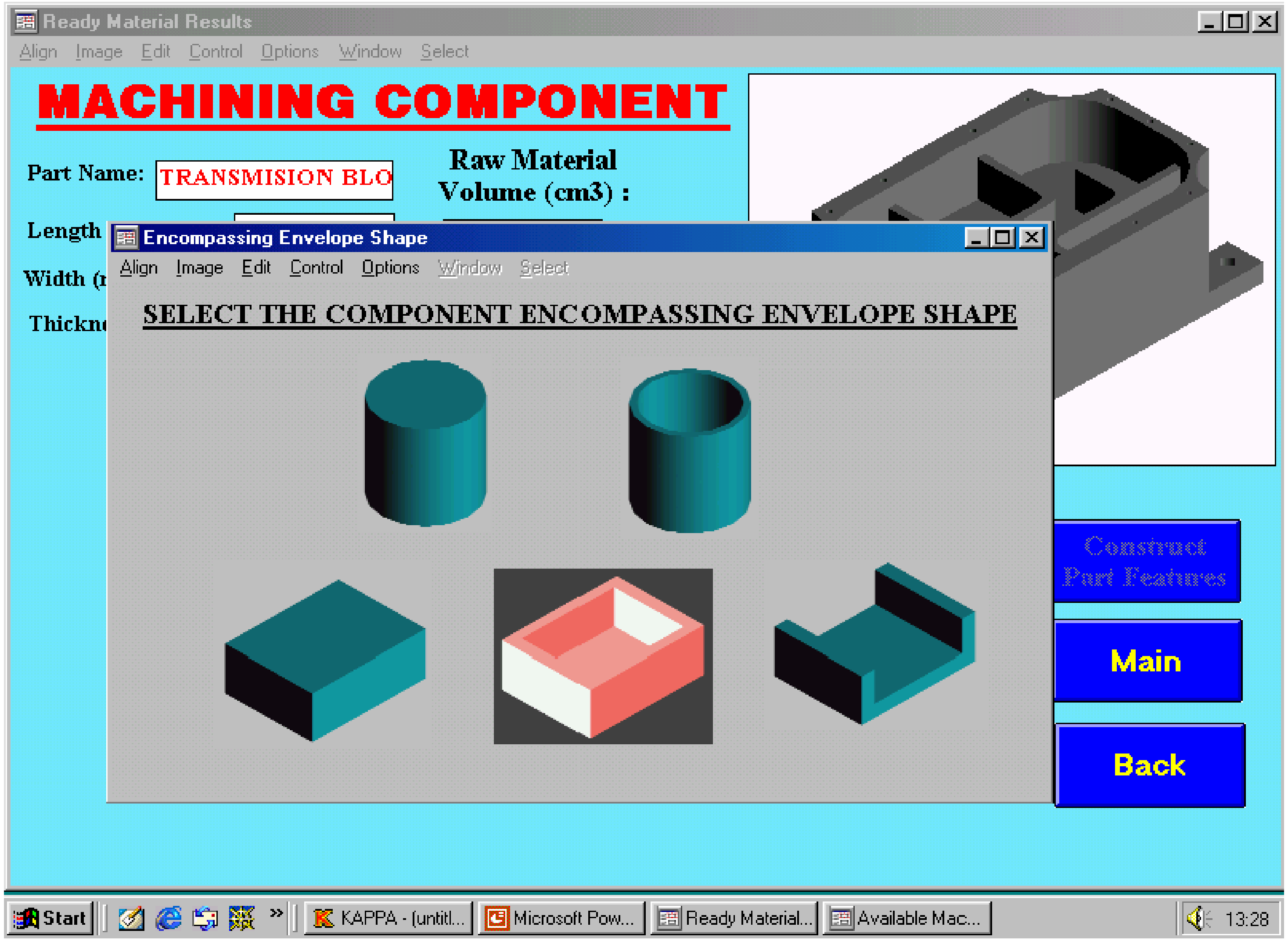


Figure (3.4) An Example of User Selection Window

3.5 System Scenario / Implementation

The procedure for cost-effective product design, using this system, requires that the designer interacts with the CAD system to construct a component and its features. The component envelope dimensions and its volume are retrieved from the database of the CAD system. A working scenario of the system is shown in Figure (3.5). There are three main modules in the developed system, cost modelling for machining processes module, cost modelling for injection moulding processes module, and design for assembly (DFA) module. The system is designed to provide the users with option of either running the entire integrated system or operating the individual modules separately. In order to select a material, this module enables the designer to input the component material based on his own criteria or to select a material from the Cambridge Materials Selector (CMS) software. The system provides recommendations when the proposed design cannot be made with the available manufacturing resources. It displays a feature-by-feature manufacturing time and cost estimation report for the designer. Additionally, the system gives a summary of the total manufacturing time and cost required for producing a component. A complete scenario of the machining and injection moulding processes is presented in Chapter 4.

If the designer would like to carry out further analysis for assembly of the product, he/she has to run the DFA module. The designer enters the production data such as production volume, number of shifts, and annual labour cost, which enable the system to select the most economic assembly technique. The recommended assembly method is determined in the early stages of the design process. The system provides the designer with the capability to estimate both the assembly time and cost for the product. In addition, a design analysis for automation and design improvement is provided in this module. A detailed procedure on how to use this module is discussed in chapter 5.

The tangible benefit of implementing this system is that the product manufacturing cost can be estimated at the early stage of the product development cycle. Therefore, a quicker response to customers' expectations is generated. One of the advantages of this system is that it warns users of features that are costly and difficult to manufacture with

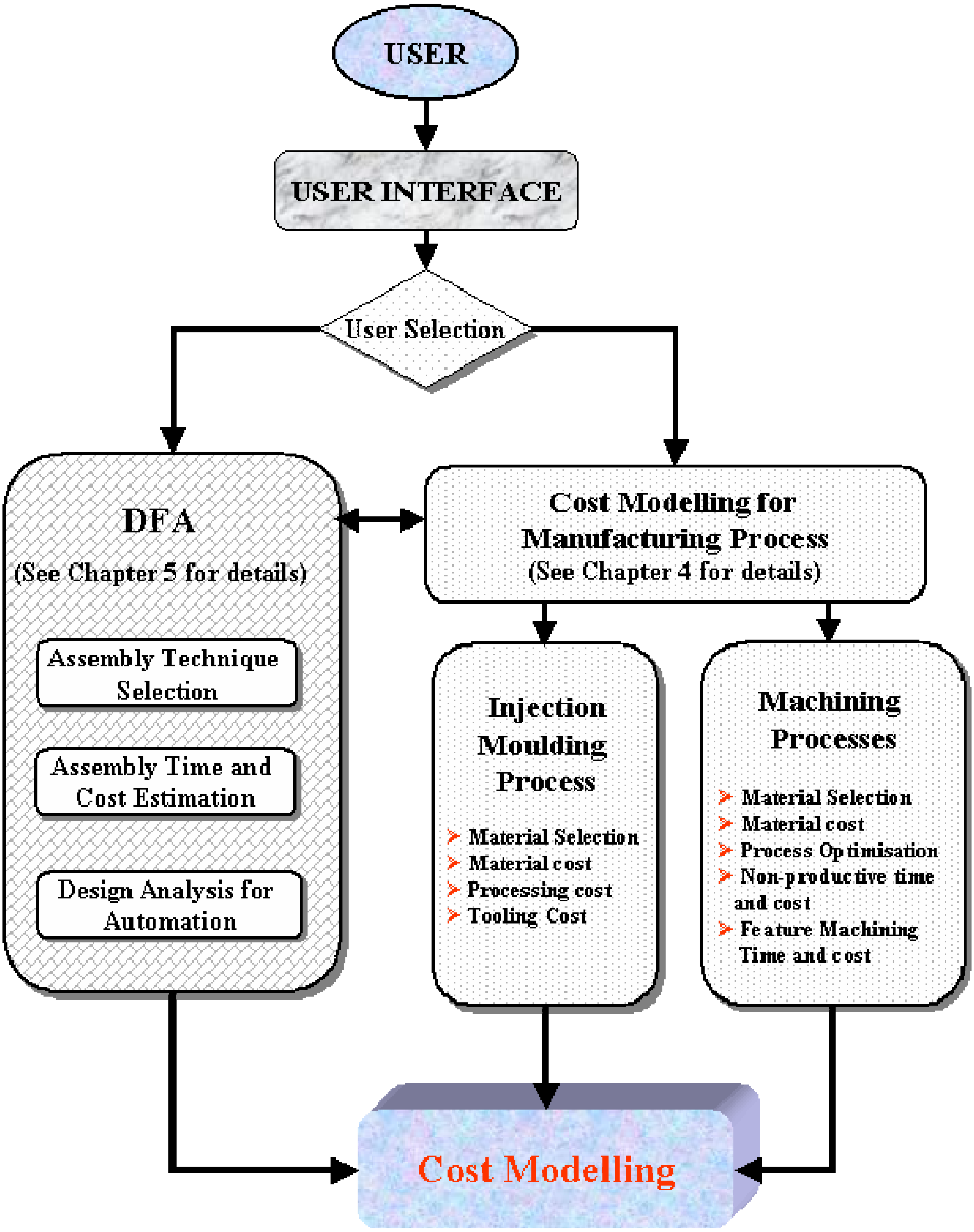


Figure (3.5) System Scenario

the available manufacturing facilities. The main function of the system, besides estimating the cost of production, is to recommend appropriate machining processes, their sequence and machining parameters in order to meet product specifications. These recommendations are based on the manufacturing resources and capabilities that the user provides to the system. It enables designers/manufacturing planners to reduce unnecessarily downstream manufacturing costs thus reducing total product cost and product lead-time. The provision of manufacturing costs, at the design phase, provides an important communication link between the design activity and downstream manufacturing activity. The evaluation procedures of the system will be outlined in chapter 6.

3.6 Summary

The proposed approach, which is presented in this chapter, provides a unique approach to product cost modelling and design for automation. It comprises of a CAD (computer aided design) solid modelling system, a material selector software, user interface, various knowledge-based system, process optimisation, databases, design for assembly module and cost estimation technique module. This chapter has outlined some of objectives that have been set out in Section 1.5 by including the following features in the proposed approach:

- Concurrent consideration of downstream activities in the early design stages to achieve product cost modelling, product designs, producible with available manufacturing resources, reduced lead-time and high quality.

- Cost modelling of both machining processes and injection moulding process, which is a process that gives high production rates, excellent quality and accuracy of products, and low manufacturing cost, has been considered in the proposed system.

- Full integration with the Cambridge Materials Selector (CMS) software, to facilitate the material selection process. It has also the capability to retrieve automatically the component envelope dimensions and volume from the database of the CAD system.

- A combination of various cost estimation techniques including heuristic data, algorithmic technique, and fuzzy logic approach.

- A user -friendly interface for providing the users with an interactive design and cost estimation environment to enable them to interact with the system easily via the utilisation of powerful features such as multiple-choice menus, images, sessions, and pop up windows.

- State of the art knowledge representation techniques offered by Kappa-PC, such as OOP, frames, and production rules, to represent the various knowledge in the system, in a systematic and well-organised way to provide an effective interaction and communication between design and manufacturing areas.

- Design analysis for assembly module provided the user with the recommendation of the most economic assembly for a product. It has the capability to estimate the assembly time and cost for the various assembly methods. It enabled designers with the ability to analyse the design for automated assembly.

CHAPTER 4

4 COST MODELLING OF MANUFACTURING PROCESSES

4.1 Overview

The development process of the manufacturing cost modelling system is presented in this chapter. Cost modelling of both machining processes and the injection moulding process, which is a process that gives high production rates, high quality and accuracy of products, and low manufacturing cost, are considered in this research. A combination of cost estimation techniques, namely, heuristic data, algorithmic approach, and a fuzzy logic approach were implemented in the developed prototype system. Five case studies were used to validate the developed system.

4.2 Introduction

Concurrent Engineering (CE) is a philosophy, which aims to increase industrial competitiveness by shortening product development time, improving quality and decreasing costs. One of the aims of CE philosophy is to utilise all information about the product life cycle simultaneously and as early as possible to avoid or reduce expensive iterations. Therefore, devoting a greater effort to design to cost is a necessary step towards optimising product costs. Thus, estimating manufacturing cost in the early stage of the design process is a very important task. This ensures that, designers can modify a design early to achieve proper performance as well as reasonable cost and it also encourages designers to design to cost. To ensure maximum productivity, it is necessary to provide accurate cost estimation of the product. As stated in Chapter 2 there has been little research effort carried out on manufacturing cost in the early stages of the design process (Ou-Yang and Lin (1997)). It was pointed out that over 70% of the total product cost was incurred at the design stage (Shehab and Abdalla (2001c) and Ou-Yang and Lin (1997)).

Existing methodologies and tools for cost estimation, process selection and optimisation have been unable to provide cost information directly to the designers (Asiedu and Gu (1998)). There are many constraints related to component features, feature-process relations, machine tools, cutting tools, cost and time in concurrent product development process. Every aspect of the product life cycle has an impact on process cost.

In order to reach a cost effective design, the factors that affect the cost of a component, such as material cost, tooling cost, manufacturing method, cost of tolerance and surface finishes for selected manufacturing method have to be considered at the design process. It can be seen as a process consists of a series of tasks that transforms a non-economically producible component geometry into an economic one. To fully analyse and model such a complex activity, activity or process analysis and modelling techniques are required (Chen and Liu (1999)).

4.3 Cost Modelling for Machining Processes

In recent years increased competition has led to an increased demand on designers to design to cost as well as for functionality. But product designers are mainly concerned about their products' performance and functionality and rarely take manufacturing and cost effectiveness' constraints into consideration at the design stage. Therefore, they need a cost-modelling tool that supports them during the design process. To date a comprehensive methodology for feature-based cost modelling has not been developed. In this section, a cost modelling for machining processes is presented. The proposed model is applied before final design details and production planning steps are available, so that it can be used at an early design stage and consequently redesign cost and longer lead-time can be avoided.

4.3.1 System Framework

To obtain an appropriate estimation of manufacturing costs, an initial process plan should be used. The initial process planning includes generation and selection of machining processes, their sequence, and their machining parameters. The machining parameters comprise of cutting tool type and cutting conditions (e.g. feed rate and cutting speed). In order to ensure this, the proposed system generates feasible process plans from the associated information of a component design, machine tool and cutting tool, and material data. The framework for cost modelling of a machined component consists of feature-based CAD system, material selection/costing module, process/machine selection, user interface, manufacturing times module, and cost estimation techniques. The basic structure of the system is shown in Figure (4.1). Each module in the proposed system interacts with one another.

A model of the component is constructed by the designer using the CAD system. The component's envelope dimensions and its volume are retrieved from the database of the CAD system. The designer has to specify all the features of the component and their attributes. The features data are saved in the feature specification of the process/machine selection module.

The system then prompts the user to select the material for the product by running Cambridge Material Selection (CMS) software, Granata Design Ltd (1994) and retrieves the necessary data of the selected material or by specifying the material based on the user's own criteria. The material properties are forwarded to the cost estimation module, in order to compute the material cost. The selection and optimisation of machining parameters are carried out through a series of interactions between various modules including feature specification database, feature manufacturing process knowledge-based, machine database, and machinability database. The data, used to identify each feature, are passed to the feature machining time function, in order to compute the required machining time for the feature. The system displays the default parameters of production and machine parameters and based on the user’s response, estimates the unit time cost, non-production time and set up time accordingly. The unit time cost is stored in the machine database.

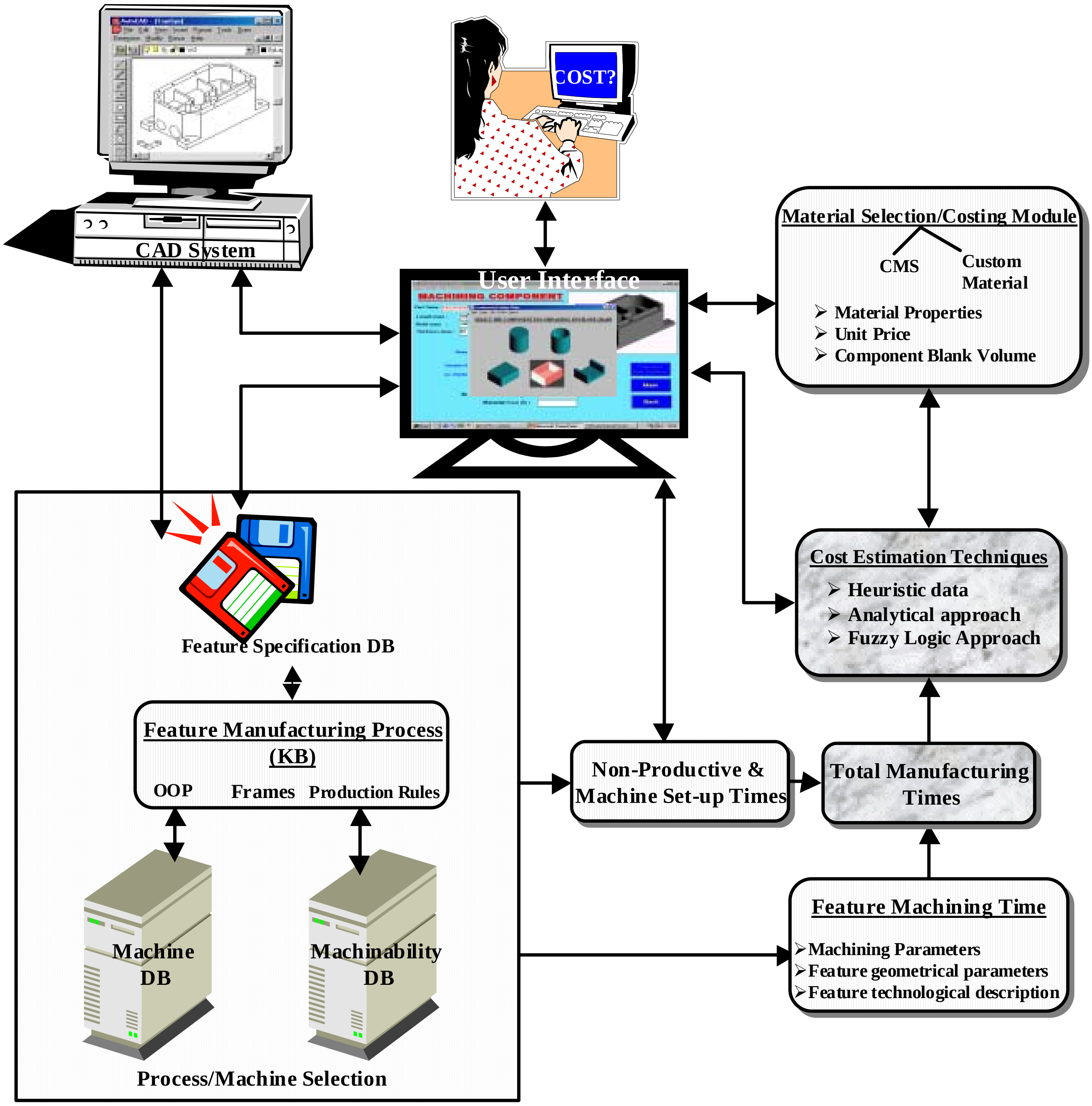


Figure (4.1) The Architecture of the Proposed Cost Estimation of Machining Components Module

The final function is to compute the manufacturing cost for the component. The data required to perform this task are the total manufacturing time for producing the component and the unit time cost of the assigned machine from the machine database. The total manufacturing times includes the machining time for each feature, the non-productive time and machine set-up time. Detailed descriptions of each component in the proposed framework are set out in the following sections.

4.3.1.1 Process/Machine Selection

The process/machine selection module, as shown in Figure (4.1), consists of a feature specification file, machine specification database, knowledge-based of the feature manufacturing process, and machinability database. The feature specification file is used to save data on the individual features of a component such as the volume and the defined parameters. Table (4.1) shows a sample file of the feature specification database for the various parameters used to define each feature. The parameter type is varied according to the different kinds of feature. The machining specification database stores related data on the available machines and the kind of operations, that can be performed by each machine, the surface finish and tolerance ranges for individual machines, and the operating cost for each machine. A sample of the machining tools database is illustrated in Table (4.2). The machinability database contains information on machinability of the work material, Brinell hardness, recommended cutting speed and feed rate. The machine data and machinability are obtained from machining data handbooks (e.g. Machining Data Handbook (1980), Machinery's Handbook (1996)). Table (4.3) shows a sample of machinability database for rough milling operation. The feature manufacturing knowledge-based contains the manufacturing processes required to produce certain features with different surface finish and tolerance requirements.

Feature ID	Feature Name	Feature Type	Dimension Type	Value (mm)	X_Distance (mm)	Y_Distance (mm)	Z_distance (mm)	Tolerance (mm) ±	SurfaceFinish (µm)
T5001	Thread	Internal	Diameter Pitch T_Depth Length	15 2.0 1.5 30	95	40	0	0.2	0.8
C4001	Chamfer	Through	Length Width Height	8.0 8.0 65	120	55	0	0.01	2.2
P3001	Pocket	Sharp Corner	Length Width Height	24 21 5.3	150	65	0	0.2	2.2W 2.2B
H1001	Hole	Blind	Diameter Depth	15 43	95	40	0	0.01	2.2
S2001	Slot	Block	Length Width Height	82 40 35	80	23	0	0.01	0.8W 0.2B

Table (4.1) An Example of the Feature Specification Database

Operation	Machine ID	MaxSurfaceFinish (µm)	MinSurfaceFinish (µm)	UnitTimeCost (£/hr)
LBM	L001	6.35	0.81	86.10
EDM	E001	6.35	0.81	30.03
Milling	M001	6.50	0.80	20.44
Drilling	M001	3.50	1.60	20.44
Drilling	D001	6.50	1.60	6.25
Boring	B001	0.40	0.40	6.25

Table (4.2) A Sample of the Machine Tools Database

MaterialName	MaterialID	Hardness BHN	DepthOfCut (mm)	CuttingSpeed (m/min)	Feed/Tooth (mm)
Grey cast iron	MFECGG_£££	120	3.80	56.39	0.406
(BS grades 100 to 400)		320	0.64	15.24	0.127
Steel,	MFECSLC£££	100	6.35	25.91	0.127
Low Carbon		150	1.27	30.48	0.178
Steel,	MFECSMC£££	125	6.35	22.86	0.127
Medium carbon		175	1.27	27.86	0.178
Aluminium alloys	MALW___£££	30	6.35	304.80	0.559
(wrought)		150	0.64	274.32	0.254

Table (4.3) A Sample of the Machinability Database

4.3.1.2 Machining Times Modules

Machining operations times are usually divided into set up times and run times. The run time is the time required to complete each component. In general, the non-productive and set-up time tend to be the most significant components of machining time, which implies that the shorter the non-productive and the set-up time, the lower the machining cost. Therefore, the total manufacturing cost is computed by adding the machining cost, material cost, set up and non-productive costs.

The feature machining time function is used to estimate the required manufacturing time for each feature. However, the machining time for some features such as, threading a hole, is obtained from Ostwald (1988) that is based on the thread pitch and workpiece material. The machining time is calculated, based on the material removal volume and specified surface roughness of each feature.

The set up time is the time required to establish and adjust the tooling, to set speeds and feeds on the metal removal machine, and to program for manufacture of one or more identical or similar components. Set-up times for various machine tools were obtained from machining handbooks (Machining Data Handbook (1980), Machinery's Handbook (1996), Bralla (1986), and Ostwald (1988)) and were used to estimate set-up costs, in order to obtain a more accurate cost estimation. The set-up time must be divided by the batch size in order to obtain the set-up time per component.

Non-productive times (costs) are incurred every time the workpiece is loaded into (and subsequently unloaded from) a machine tool. The non-productive costs would be quite small, if one machining operation and one pass are used to produce a component. On the other hand, when a series of machining operations are used, the non-productive costs accumulate and become a highly significant factor in the machining cost. In each case the tool must be repositioned, perhaps the feed and speed settings changed and then, when the operation is completed, the tool must be withdrawn. Therefore, the time for tool engagement or indexing must be taken into account.

The total manufacturing times include machining time for each feature, the non-productive time and machine set-up time. The estimated manufacturing time is used to compute the manufacturing cost of the component. Then, the computation results for the various elements of manufacturing times and cost estimation are prompted to the user in a well-designed report.

4.3.1.3 Feature-Based Modelling (FBM)

Feature-based modelling (FBM), sometimes referred to as a feature technology, describes a product as the aggregation of features and feature relationships. However, a feature is defined as a generic entity which possesses product information, which may be used for design or communication in a design, manufacturing and other engineering tasks such as assembly, manufacturing, process selection, cost/time estimation and maintenance. The representation of the features should be explicit in a form that

matches manufacturing knowledge. Analysis of the form features, directly associated with certain machining process, has an important effect on generating a process plan. In this analysis, manufacturing form features were selected as the lynch pin for the generation of the machining processes and estimation of manufacturing costs. The use of manufacturing form features helps designers to simplify process planning without consideration of component manufacture. Therefore, the feature-based representation technique has been used to represent the component and its features in a greater detail. Cost effective process planning can be achieved by the definition of manufacturing form features that are derived from topological and geometrical description of the component. For instance, a hole is form feature defined by its parameters such as its identification number (ID), name, diameter, depth, locations, tolerance, and surface finish. Based on these parameters the machining processes, set-up, fixtures, cutting tools and cutting parameters can be chosen. Consequently, the machining time and cost can be estimated.
In the present system, manufacturing form features are represented by using an object-oriented representation technique. The feature parameters are then passed to the feature specification database.

4.3.1.4 Knowledge Representation Approaches

Knowledge representation is the description of the knowledge with symbolic encoding. It deals with how to organise and encode knowledge in the best form so that problems can easily be solved. Many representation techniques, such as production rules, object orientation and framework have been reported in AI, to meet the requirements for specific problems.

Hybrid knowledge representation techniques are employed to represent manufacturing knowledge in this research. These techniques, such as production rules, frame and object oriented are described in detail as follows.

4.3.1.4.1 Production Rules

Knowledge and facts about a problem domain can be represented as a rule in the form **IF** premises **Then** conclusion**.** In the proposed system, several rules classes have been developed and connected to each other. In this case, the conclusion of one rule is included in the premise of another rule. This technique is called chaining. When chaining commences, conclusions of one rule class match the premises of another rule class. Chaining is used either in a forward or backward direction. For example, the selection of the appropriate operation to make a particular feature according to the predefined rules or constraints is shown in the following rules:

POCKET_MAKING_RULE1:

IF

(The component material is metallic) *AND*

(The Feature is a pocket) *AND*

(The pocket corner is sharp) *AND*

(The surface finish <6.35μm) *AND*

(Additional rules)

THEN

(E001 is selected)

E001 is an electric discharge machining (EDM) that uses for producing sharp corner pockets and fine holes.

HOLE_MAKING_RULE1:

IF

(The feature is a hole) *AND*

(The diameter of the hole <3 mm) *AND*

(The aspect ratio 'depth over diameter' >5) *AND*

(The aspect ratio 'depth over diameter' <100) *AND*

(The tolerance of the hole <0.0125 mm) *AND*

(Additional rules)

THEN

(E001 is selected)

SLOT_MAKING_RULE1_1:

IF

(The feature is a slot) *AND*
(The width of the slot > 4 mm) *AND*
(The tolerance of the slot > 0.01 mm) *AND*
(Additional rules)

THEN

(M001 is selected) *AND*
(RoughMilling is selected process)

M001 is a milling machine.

SLOT_MAKING RULE1_2:

IF

(The feature is a slot) *AND*
(The RoughMilling is done) *AND*
(The surface finish for the slot base >= 0.8 μm) *AND*
(The surface finish for the slot base <= 6.5 μm) *AND*
(Additional rules)

THEN

(M001 is selected) *AND*
(EndMillingBase is selected process)

SLOT_MAKING RULE1_3:

IF

(The feature is a slot) *AND*
(The RoughMilling is done) *AND*
(The surface finish for the slot wall >= 0.8 μm) *AND*
(The surface finish for the slot wall <= 6.5 μm) *AND*
(Additional rules)

THEN

(M001 is selected) *AND*
(EndMillingWall is selected process)

4.3.1.4.2 Frames

A frame is a data structure that describes multi-dimensional data. A slot consists of multiple sides, and a side consists of multiple values. Frame, slot and side can describe various kinds of information. The frames in Kappa-PC are very flexible so that images and active values to any slots can be attached to monitor value changes. Facts as attributes of slots allow description of values of a slot and how they are passed down the hierarchy.

4.3.1.4.3 Object-Oriented Representation

Object-oriented programming systems have an inherent ability that appeals to designers, as they enable them to model real world design problems as a collection of objects. Thus, they provide the designers with an expressive power to represent complex problems or information in an effective manner. Using such a technique, design, manufacturing, and costing objects, such as machine tools, cutting tools, features, and material properties are organised into various classes represented in hierarchies. Figure (4.2) shows object oriented representation of features, manufacture processes and costs elements. A class has a name and several subclasses, consisting of a number of objects with a number of slots, attributes such as feed rate, tolerance, and surface finish. All classes can be broken down into subdivisions so that all components of the class are considered. One of the reasons for using object-oriented technique is to take advantage of its characteristics of data abstraction, inheritance, and modularity. Inheritance enables the designer to define a specific value into a higher class that can be inherited by the lowest class of the hierarchy.

4.3.1.5 Material Selection and Costing

The first step in the full analysis of a design concept is the selection of the best material to be employed. Material selection is an important stage and complicated one that is made early in the design process. The procedure of material selection was discussed in detail in chapter 3.

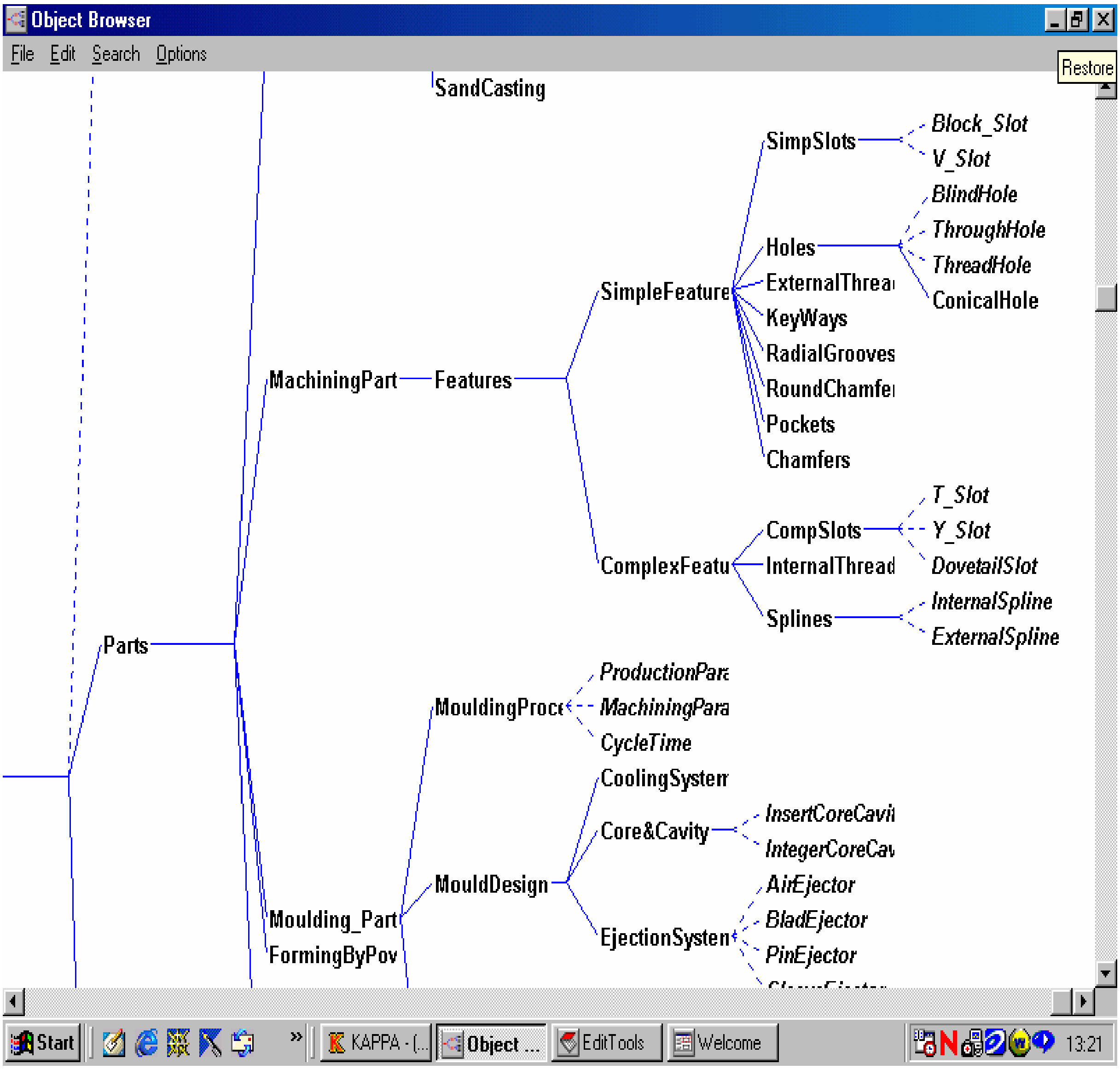


Figure (4.2) Object-Oriented Representation of Manufacture Processes, Cost Elements and Features

For a machined component, the material cost (C_{mt}) can be estimated using the following equation:

$$C_{mt} = V \quad \rho \quad C_w \qquad (4.1)$$

Where:

V = Raw Material Component volume, m^3

ρ = Material density, kg/m^3

C_w = Unit price, £/kg

The material cost will be added to manufacturing cost of the product.

4.3.1.6 User Interface

To provide the user with an interactive design environment, a user-friendly interface has been developed, as an important part of the proposed system, in order to enable the user to use the system easily and efficiently. The Kappa-PC toolkit features such as sessions, popup windows, menus and images were used to create the user interface so that the user-defined values can be used to accomplish product cost tasks. The user interface enables users to interact with a CAD system (AutoCAD) to generate three-dimensional solid models, as well as with the Cambridge Material Selection (CMS) software. The retrieved component's envelope dimensions, geometric volume and the material properties are displayed in an efficient way. The user is prompted to input the geometrical and topological attributes of the form features of the component. Based on these attributes, the system recommends the manufacturing process and the machining parameters to produce a certain feature. These recommendations are displayed on separate screens. The various elements of the product cost are reported to the user in a Kappa-PC window. Finally, the user is provided with options to clear the working memory and restart another application, make hard copy of the system recommendations and reports, or quit the system altogether.

4.4 Cost Estimation Techniques

There are many problems in production systems where a decision needs to be taken in uncertain situations. The estimation of expected cost of a product in a manufacturing system is one such problem. The various cost terms are fluctuating in the real-world situation. In such situations, where the heuristic data are not available, algorithmic or fuzzy logic techniques can be used. Therefore, the developed system allows users to generate accurate cost estimates for new designs and explore alternative materials and process.

4.4.1 *Algorithmic Technique*

The required machining time and cost for the component are computed based on the methodology developed by Ou-Yang and Lin. (1997).

1 Computation of the required machining time for each operation:

$$T_{ij} = k_j \prod_{k=1}^{n} p_{ijk} \qquad (4.\ 2)$$

Where:

T_{ij} = Time required to accomplish the machining operation *j* of feature *i*,

k_j = Coefficient for the operation j,

p_{ijk} = The value of a parameter or the reciprocal of a parameter used in defining feature i

2 Computation of the required machining cost for each operation.

$$C_{ij} = M_h T_{ij} + S_h \qquad (4.\ 3)$$

Where:

C_{ij} = The estimated machining cost for the operation *j* of feature *i*

M_h = Unit time cost (£/min) for machining *h* (machine *h* is selected to perform operation *j)*

S_h = Set-up cost for machine *h*

3 Estimation of the required machining cost for each feature

$$FC_i = \sum_j C_{ij} \qquad (4.4)$$

Where:

FC_i = The estimated machining cost for each feature *i*.

4. Computation of the required machining cost for each component

$$TC = \sum_i FC_i \qquad (4.5)$$

Where:

TC = The estimated machining cost for the component.

Set-up times for various machine tools were obtained from machining handbooks such as Machining Data Handbook (1980), and were used to estimate set-up costs, in order to obtain a more accurate cost estimation. In addition, the system allows the users to input their data. The total manufacturing cost is computed by adding the machining cost, material cost, set up and change over costs.

4.4.2 Fuzzy Logic Approach

With fuzzy logic, manufacturers can significantly reduce development time, model highly complex non-linear systems, deploy advanced systems using control engineers rather than control scientists, and implement controls using less expensive chips and sensors (Cox (1994)). For many knowledge engineers a significant benefit of fuzzy system modelling is the ability to encode knowledge directly in a form that is very close to the way experts themselves think about the decision process. The following sections will: (1) outline the basic steps to develop a fuzzy logic model, (2) present a fuzzy logic model for cost estimation.

4.4.2.1 An Overview for Building a Fuzzy Logic Model

Fuzzy logic has been used as the basis for controlling industrial processes and consumer products such as cameras, washing machines, and automotive systems. This is because it does not require the use of complex mathematical models. It reduces development time and can be implemented with less expensive microprocessors. The difference between a fuzzy expert system and the traditional expert system is that the reasoning process used to reach conclusions is different. In the case of the expert system, production rules are used to characterise various knowledge. Production rules capture knowledge in the form of "**IF** premises **Then** conclusion" statements. A fuzzy production rule is similar to the traditional type of production rules except that the conditions in the production rules are replaced with linguistic expressions to which truth-values are assigned. In addition, fuzzy models require fewer rules than conventional systems and these rules are closer to the way knowledge is expressed in natural language. This has two important side benefits for model maintenance engineers. Firstly, a model can generally be modified with fewer induced errors. Secondly, the relative simplicity of a fuzzy model means that logic or structural problems can be located and fixed in a minimum amount of time.

The main process in a fuzzy model is to identify the various input and output model variables. A model variable is often described in terms of its fuzzy space. This space is generally composed of multiple, overlapping fuzzy sets, each fuzzy set describing a semantic partition of the variable's allowable problem state. This total problem space, from the smallest to the largest allowable value, is called the *universe of discourse.* The fuzzy sets describing this universe of discourse need not be symmetric but they will always overlap to some degree. The amount of overlap must vary between 10 to 50% (Cox 1994)). Note that the universe of discourse is associated with a model *variable*, not with a particular fuzzy set (the range of an individual fuzzy set is the domain). Each overlapping fuzzy region is assigned a term name so that it can be referenced in the model. Fuzzy sets are actually functions that map a value that might be a member of the set to a number between ‘zero’ and ‘one’ indicating its actual degree of membership. A degree of zero means that the value is not in the set, and a degree of one means that the value is completely representative of the set. The centre of the fuzzy modelling technique is the idea of a linguistic variable. At its root, a linguistic variable is the name of a fuzzy set. Rules manipulate fuzzy sets.

However, a fuzzy model, like traditional expert and decision support systems, is based on the input, process, output flow concept. The fuzzy model differs in two important properties, what flows into and out of the process and the fundamental transformation activity embodied in the process itself. Several steps are required to develop a fuzzy logic model. These steps are fuzzification of inputs, fuzzy inference based on a defined set of rules, and finally defuzzification of the inferred fuzzy values. The main process in the fuzzy model is to assign fuzzy sets of input variables and fuzzy sets of output variables. Each variable has a number of memberships. In the jargon of fuzzy logic, a fuzzy set is a set of points on the universe of discourse for the linguistic notion, and each point is coupled with a truth value. The complete structure of developing a fuzzy logic model is illustrated in Figure (4.3). Firstly, all input variables have to be translated into linguistic variables. This step is called “fuzzification” as it uses fuzzy sets for translating real variables into linguistic variables (Altrock (1996)). Once all input variables are translated into respective linguistic variable values, the so-called “fuzzy inference” step evaluates the set of if-then rules that defined system behaviour. The result of this is again a linguistic value for the linguistic variable. Defuzzification is a critical control factor in completing the design of a fuzzy model. Defuzzification selects the expected value of the solution variable from the consequent fuzzy region. How this is done will affect the predictive performance of your model. The centroid defuzzification is commonly the only defuzzification method used in control engineering applications such as robotics. The centroid method is sensitive to the height and width of the total fuzzy region. In the “defuzzification” step, the linguistic result translates into a real value that represents the output variable.

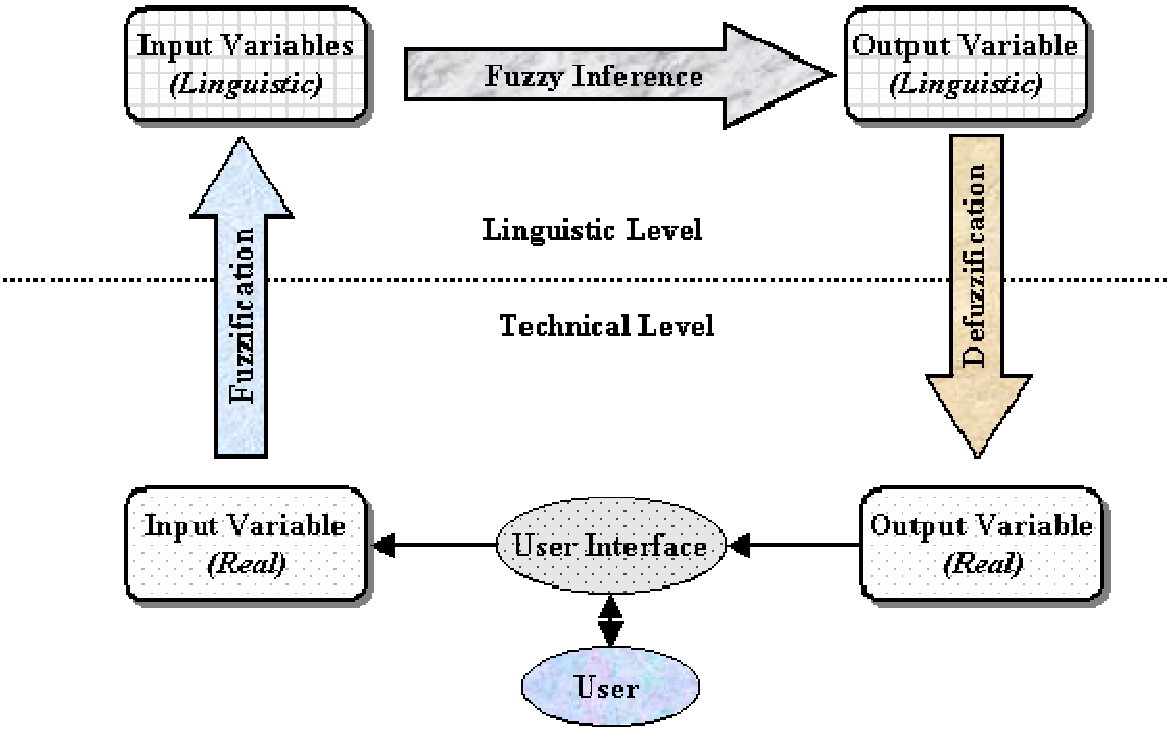


Figure (4.3) The Structure of Developing a Fuzzy Logic Model

4.4.2.4 A Fuzzy Logic Model

A fuzzy logic approach to cost estimating may be useful when the cost estimator does not have data that allows the construction of cost estimating relationships (CERs), in the traditional manner (Mason et al. (1997)). Cost estimating relationships (CERs) are mathematical models or graphs that estimate costs. The parameters used to define any feature are termed cost drivers. For example, the parameters used to define a hole are diameter and length. The cost drivers are related to costs by cost estimating relationships (CERs).

A fuzzy logic technique is applied in the developed system. The objective of this model is to overcome the uncertainty in cost estimation problems that cannot be addressed by traditional techniques. In this model, there are three cost drivers that affect the product cost. These factors are the initial component size, component shape complexity, and the required surface finish of the component. Figure (4.4) shows the structure of developed fuzzy logic model for cost modelling.

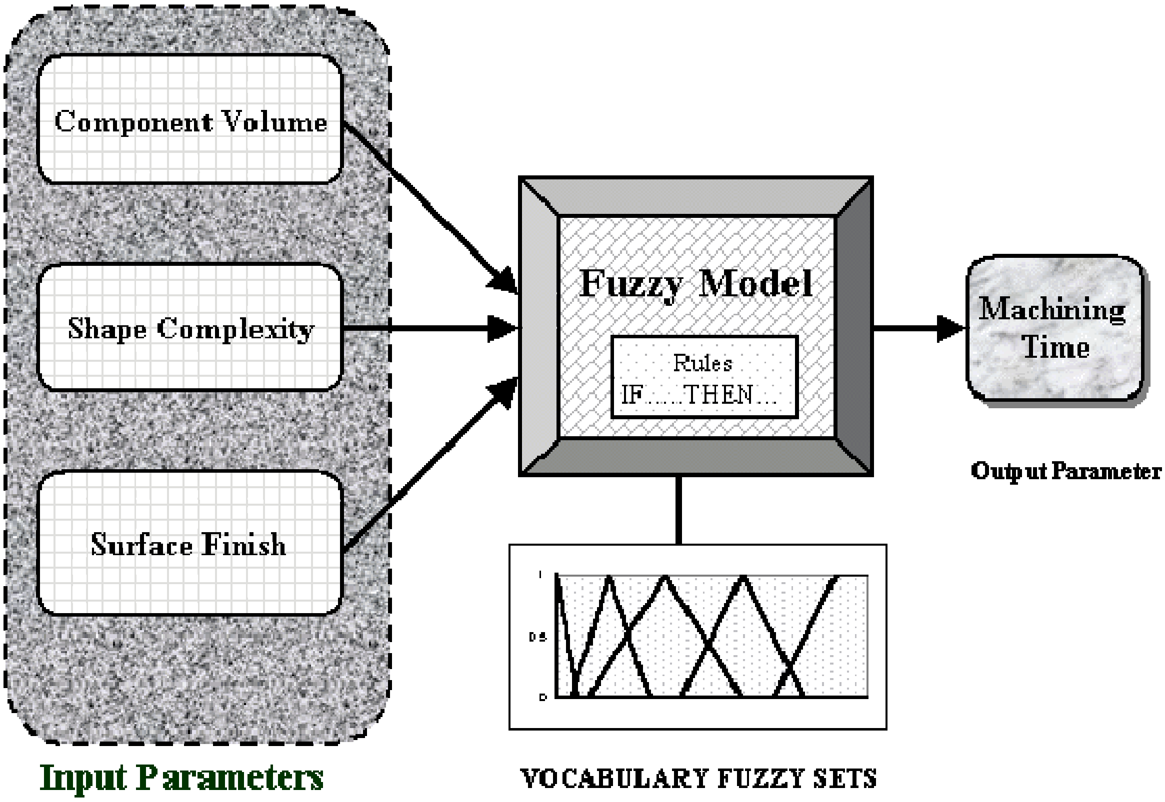


Figure (4.4) The Structure of the Cost Estimation Fuzzy Logic Model of a New Product

The input cost drivers, of the proposed fuzzy logic model, are component volume, shape complexity and surface finish. While the output variable is the machining time. Different applications of the fuzzy control technique use a specific shape of the fuzzy set which is dependent on the system behaviour identified by the knowledge engineer. So far, there is no standard method of choosing the proper shape of the fuzzy sets of the control variables (El Baradie (1997)). The most widely used shapes are triangular, trapezoidal and arcs. For example, for modelling the helmsman's action in steering a ship, the trapezoidal shape was found to be the best shape for that specific application (El Baradie (1997)). In the developed model, the triangle shape has been selected to describe the fuzzy variables for cost parameters, i.e. the component volume, shape complexity and surface finish.

Figures (4.5, 4.6, 4.7, and 4.8) show the fuzzy sets of the input and output variables. Fuzzy sets for *component volume* are very small (VS), small (SM), medium (ME), large (LA), and very large (VL). The universe of discourse of the component volume is Zero to 10000 cubic centimetres. While the domain for the fuzzy set medium is 1000 to 6000 cubic centimetres. The universe of discourse of the input and output variables are based on three main sources. These sources are open literature, discussion with technicians at De Montfort University, and interviews with manufacturing experts in selected companies. The model parameter *shape complexity* is broken down into three fuzzy sets, low (LO), medium (ME), and high (HI). A shape complexity of index on a scale of 1 to 10, as the universe of discourse will be considered in the present fuzzy model. *Surface finish* is broken into three fuzzy sets, namely, texture (TE), polish (PO), and normal (NO). The notion of membership functions for the output variable, which is *machining time*, can be identified as low (LO), average (AV), and high (HI). The universe of discourse for the machining time is Zero to 90 minutes.

A decision table is a symbolic way of representing the logical interdependence between events. Decision tables, that provide a means for system rules, can be used to indicate the relationships between the input and output variables of the fuzzy logic system. In the developed model, with three independent variables each of which consists of a number of membership functions, a (3 x 3 x 5) decision table with forty-five rules was constructed. A sample of the decision table for hole making is illustrated in Table (4.4).

Table (4.4) A Sample of the Decision Table

Component Volume	Small	Large	Small
Shape Complexity	High	Low	Medium
Surface Finish	Polish	Normal	Polish
Machining Time	High	Low	Average

The set of rules from the above decision table is:

FL_RULE1:

IF

(The component volume is small) AND

(The shape complexity is high) AND

(The required surface finish is polish) AND

THEN

(The machining time is high)

FL_RULE2:

IF

(The component volume is large) AND

(The shape complexity is low) AND

(The required surface finish is normal) AND

THEN

(The machining time is low)

FL_RULE3:

IF

(The component volume is small) AND

(The shape complexity is medium) AND

(The required surface finish is Polish) AND

THEN

(The machining time is average)

The machining cost (C_m) of the component is equal unit time cost (R_i) Multiplied by a corresponding machining time (T_i) as:

$$C_m = R_i T_i \tag{4. 6}$$

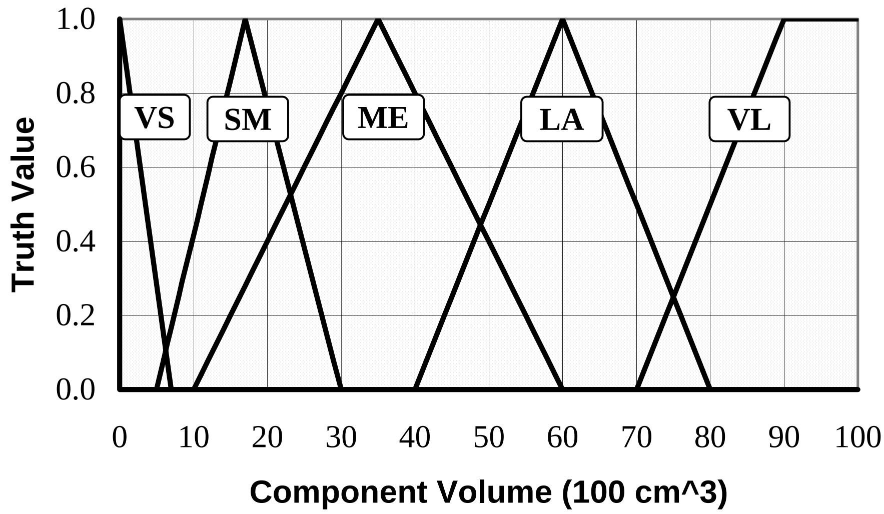


Figure (4.5) Fuzzy Sets for Component Volume

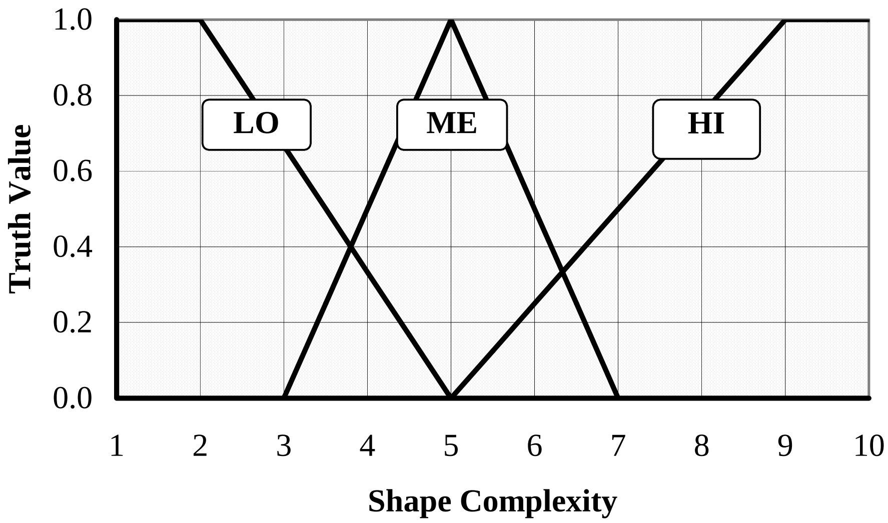


Figure (4.6) Fuzzy Sets for Shape Complexity

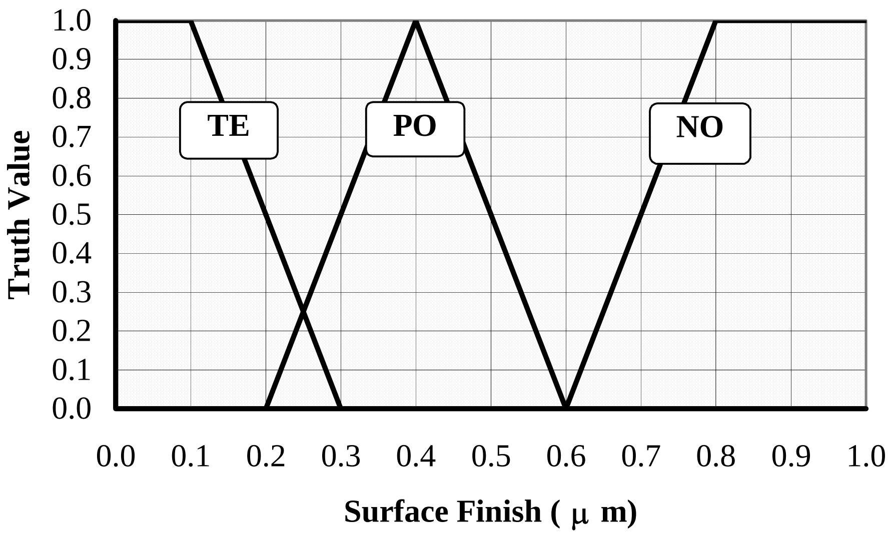


Figure (4.7) Fuzzy Sets for Surface Finish

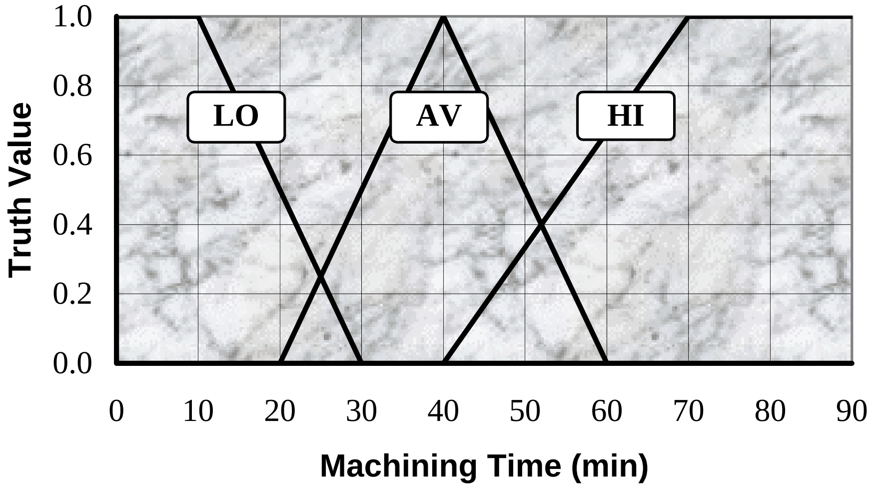


Figure (4.8) Fuzzy Sets for Machining Time

4.5 Costing Analysis Scenario for Machined Components

The scenario for machined component cost estimation is launched by specifying the production data, which enable the system to select the most economic assembly technique. The user selects the manufacturing process for the component. These include machining, injection-moulding, casting, sheet metal forming and powder metallurgy processes. Currently the system supports the first two processes. The rest will be considered in future work.
The designer constructs the component model via the CAD system. The component envelope's dimensions and volume are then retrieved from the database in the CAD system. The system prompts the user to select between two options for the material. In the first option users specify the material and its properties, based on their own criteria. While in the second option the system runs Cambridge Materials Selector (CMS) software. Hence, the proposed system retrieves all the data necessary to estimate the material cost for the component.

The designer has to specify all the features of the component and their attributes. The system prompts the user to specify the surface roughness and tolerance of each feature in the component. The feature data include the feature type and the values of the parameters used to define each feature, which are stored in a feature specification file. The system examines the manufacturability of each feature by applying the manufacturing process rules stored in the knowledge-based. Hence, for each process the system acquires a group of suitable machines from the machine database. For these appropriate machines, the system selects one, which provides a surface finish and tolerance range, to meet the required specification of the specific feature. Based on the estimated results, analysis of the feasibility of manufacturing the component from the cost point of view is carried out. If the required cost cannot meet the targeted cost, then the system may suggest reselecting a machine or redesigning the product. The estimated manufacturing costs for each component and its feature is produced and stored in the manufacturing cost module. The flowchart of the proposed cost analysis process is shown in Figure (4.9). The system enables users to select another component for cost estimation. Finally, the system estimates the assembly cost of the product based on the recommended assembly technique.

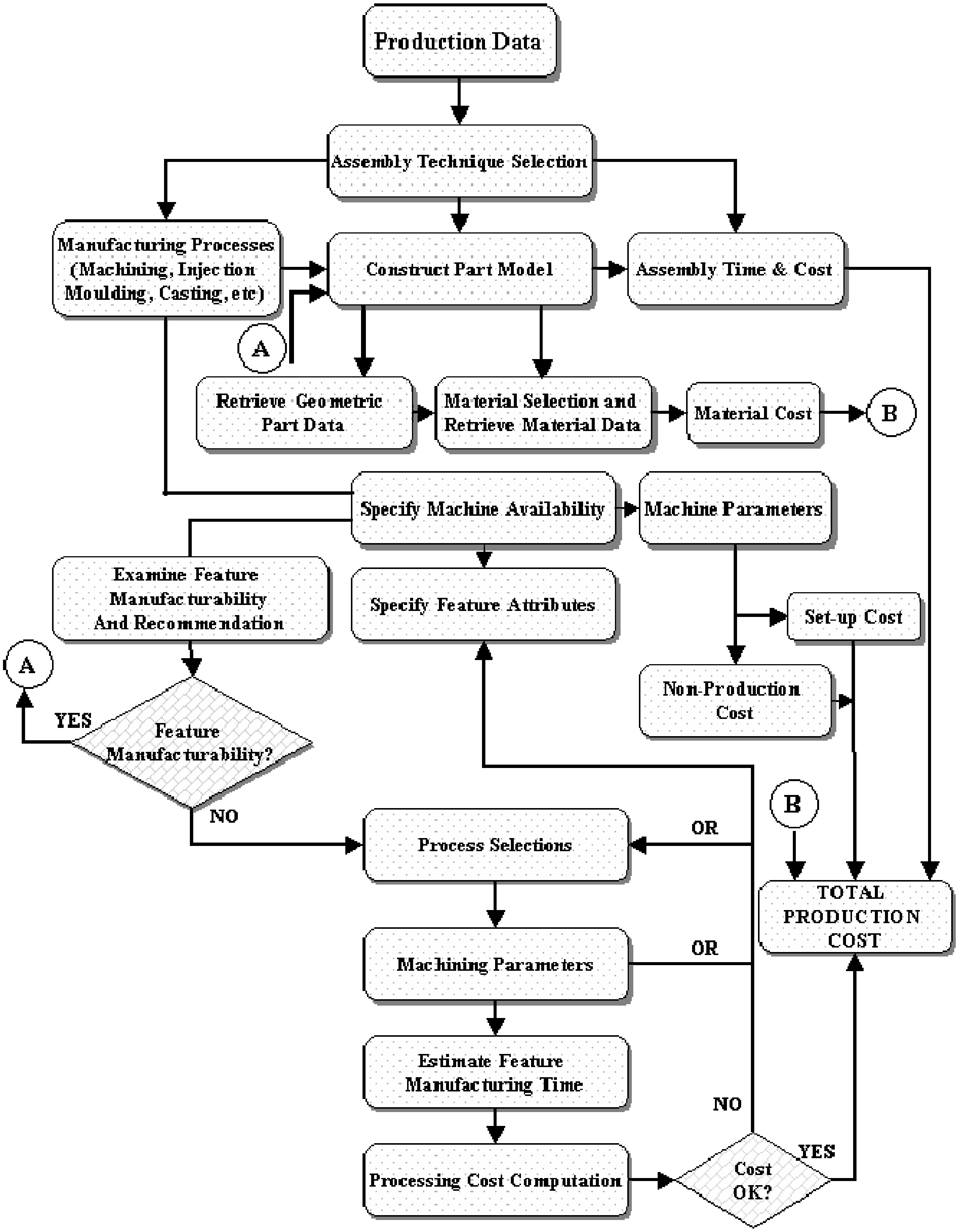


Figure (4.9) The Cost Analysis Scenario of the Developed System

4.6 Cost Modelling of Injection Moulded Components

Injection moulded components are widely used in a wide variety of industries, such as automotive, appliance, computers, communications and industrial equipment. Examples of injection moulded components in automotive industry include front panels, radiator end caps, door panels, lamp housing, and fuel rails. Injection moulding has several features that make its utilisation feasible, especially for the mass production of complicated components. These features are:

- Direct path from material to finished component
- No or minimal finishing of moulded component necessary
- Produces components which are not prone to porosity
- Process may be fully automated
- Good repeatability of production with constant weight and identical properties.

In injection moulding process, the raw material is usually in powder form, which is converted into a melt. These materials are specially formulated. The granulated material is plasticised by the rotation of the screw in a heated barrel. After closing the mould, which contains a cavity in the shape of the component to be moulded, the plasticised material is injected through an axial displacement of the screw. The temperature of the mould is less than that of the melt, so the mixture begins to set as soon as it comes into contact with walls of the mould. The melt of thermoplastic material is subsequently cooled in the mould. Finally, the mould is opened and the moulded component is ejected. During production of an injection moulded component, each step is co-ordinated by machine controls. In addition to the basic steps described above, other functions may take place such as retraction of the injection unit, actuation of cores and other applications.

Regardless of the material to be processed, an injection moulding machine consists of the machine frame, injection unit and clamping unit. The clamping unit serves to open and close the mould during the production cycle. The clamping unit, screw and injection unit are driven hydraulically. The pumps, required to provide the necessary flow of oil, are located in the machine frame and powered electrically. To activate additional functions, such as ejectors, shutoff nozzles, or core pulls, simple electromechanical or pneumatically driven devices are incorporated. The moulding compound must be cooled to below the solidification point, before the moulded component can be removed.

This section deals with estimating the manufacturing cost of injection-moulded components. A full understanding of the characteristics of moulding product development process will facilitate product cost analysis. In the following subsection, the conventional moulding product development process, with an emphasis on the identification of cost factors, is reviewed. Based on the results of this process characterisation, a cost model is developed.

Injection moulding product design includes conceptual design, preliminary design, parting line/planes design and detail design (Rosato and Rosato (1996)). In conceptual design, a sketch or a conceptual model is configured based on the products functional requirements. Preliminary design deals with the initial product geometry, specifications and performance requirements. Detail design refines the preliminary product geometry into a shape that is functionally acceptable and compatible with the injection moulding process.

Process development activities influence the product design. Process design determines moulding process parameters such as clamping force, heating temperature, and injection speed. The results from the process design determine manufacturing cycle time and the overall manufacturing maintenance and support costs, which in turn affect the cost of the product.

4.6.1 Moulding Product Cost Analysis

Product costs are influenced by the number of components being produced, the material being processed, tooling costs, process cycle times, and the amount of scrap generated. This research focuses on all the related cost factors that directly affect the cost of individual products. The manufacturing cost of an injection-moulded component is largely made up of three main cost elements, namely mould cost, material cost, and processing cost. These three elements are illustrated in Figure (4.10). The component's size, geometric shape and material influence these three costs.

Material cost can be estimated from the weight of the component plus an allowance for material waste. The cost of allowance for material waste includes tare costs, scrap costs, and in-plant processing costs. The tare material can be re-melted and used for other moulded products. The tare costs are associated with spurs, runners and overflows because they are not recoverable. Scrap includes warm-up shots, in-plant rejects, and returned components.

Mould basically has two sets of components, the cavities and cores, and the base in which the cavities and cores are mounted. The mould determines the size, shape, dimensions, finish, and often the physical properties of the final product. Mould design involves shrinkage design, cavity and core layout, parting line determination, feed system design, cooling system design and ejector design. The mould costs include mould base, and manufacturing of the mould. The cost of the mould base depends on factors such as moulding material, component size and complexity, final product cost, number of cavities and wall thickness.

The processing cost per moulding is obtained from the set-up cost and machine cycle time. The cycle time and production yield are important cost parameters. The production yield is the percentage of saleable mouldings, which is the total product minus mouldings that will eventually be scrapped divided by the total number. The processing cycle time consists of the machine opening and closing time, injection time, cooling time and ejection time. The cooling time normally accounts for more than two thirds of total cycle time. Uniform cooling improves the component quality by reducing residual stresses and maintaining dimensional accuracy and stability. The cooling time is a function of component wall thickness, the candidate material properties, and the mould temperature.

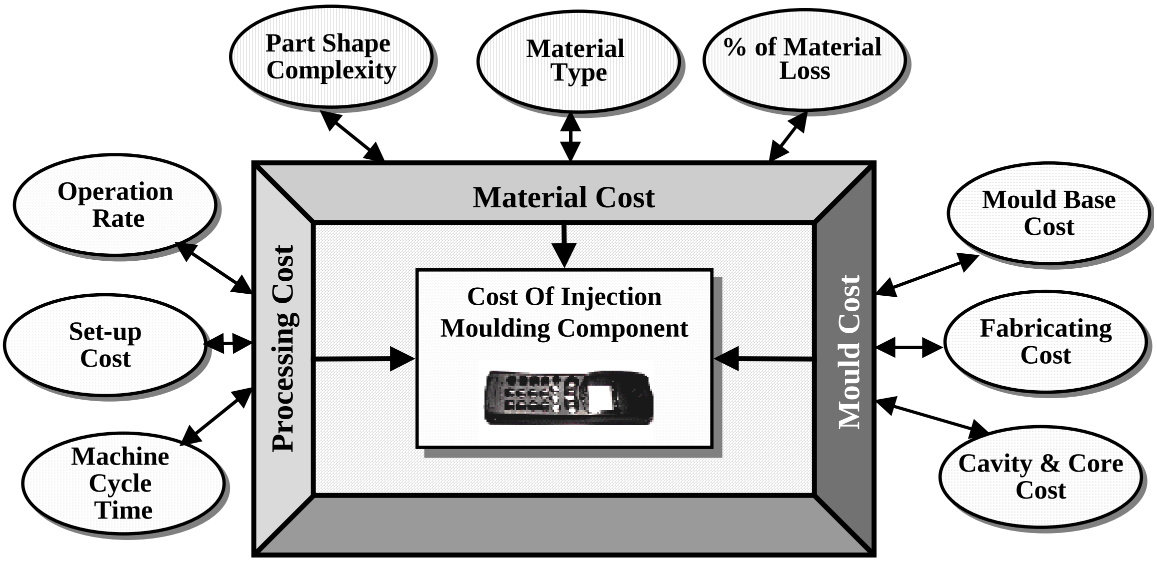


Figure (4.10) The Cost Structure of a Moulded Component

4.6.2 Manufacturing Cost Model for Moulded Components

The framework for manufacturing cost of a moulded component consists of the material selection environment, CAD system, injection process environment, user interface, and mould design. This framework is illustrated in Figure (4.11). The function of the CAD system is to support the feature-based component construction and modification function for the user to perform the design task. Material selection is an important stage and complicated task that is made early in the design process. Therefore, the selection of a material is a critical design decision that should be fixed before a material's compatibility with other aspects of design is evaluated. Material selection depends to a large extent on the functional constraints of the component, wall thickness, final component cost, and mould design. The material environment is composed of material selection, material database and material cost estimation. The material database is used to store the retrieved material data from CMS of the candidate material. The material data are used to compute the material cost.

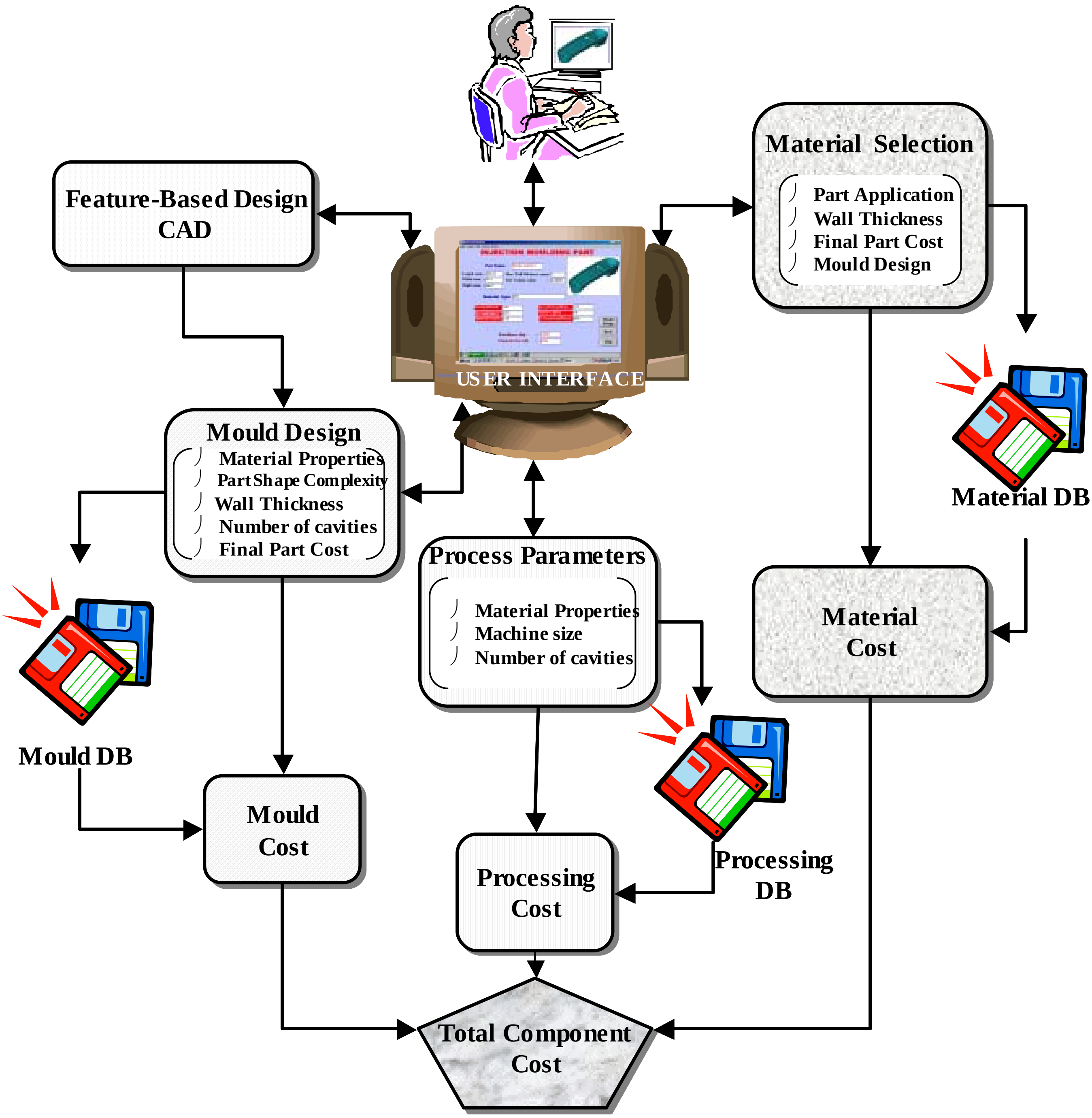


Figure (4.11) The Manufacturing Cost Framework of a Moulded Component

The mould design is strongly affected by material properties, number of cavities, component shape complexity and wall thickness. Three factors primarily influence the choice of wall thickness for a component. These are component design for stiffness, cooling time, and flow length. The allowable deflection of a flat plate or other simple geometries will determine the wall thickness. High strength materials may permit thinner wall sections. On the other hand, a thinner wall can inhibit the component to be filled. The mould cost depends mainly on the cost of mould base and the costs of manufacturing the cavity and core.

The processing cost is obtained from the set up cost, machine rate, and processing cycle time. The machine rate is determined by the cost of the machine and the method of machine amortisation. The processing cycle cost time usually consists of the injection or filling time, the cooling time, and the machine resetting time.

4.6.2.1 Material Cost

The main elements of the material cost are the weight of material required per component and the unit cost of the candidate material. In the injection moulding process, an allowance for material waste such as tare and scrap must be considered in the material cost estimation. From the component volume, material properties and percentage of material loss, the material costs are computed from the following form proposed by Shing (1999):

$$C_{mt} = V_p * \rho * C_w * (1 + \frac{f}{100}) \qquad (4.7)$$

Where:

C_{mt} = material cost , £/component

V_p = component volume, m^3

ρ = material density, kg/m^3

C_w = unit price, £/kg

f = percentage of material loss.

4.6.2.2 Mould Cost

The main constituents of mould costs are the cost of mould base, number of cavities, and the fabrication of the cavity and core inserts. The system prompts the user to enter the number of cavities. Based on this number and the component envelope dimensions data retrieved from the CAD system, the system estimates the mould base envelope dimensions. These data are used to estimate the total cost of manufacturing a mould using the following form (Shing (1999)):

$$C_{mc} = C_{mb} + C_{c1} * n^{m} + C_{oc} \qquad (4.\ 8)$$

Where:

C_{mc} = total mould manufacturing cost, £

C_{mb} = mould base cost, £

C_{c1} = cost of fabricating one cavity and core inserts , £/inserts

C_{oc} = other fabricating cost, £

n = number of cavities,

m = multicavity cost index.

4.6.2.3 Processing Cost

The injection moulding processing cost is the sum of the set up cost and machine cycle time cost. This element of the moulded component cost can be estimated from the following equation (Shing (1999)):

$$C_{pc} = \left(\frac{T_{su}}{N_{bs}} + \frac{T_{cy}}{ny}\right) R_{op} \qquad (4.\ 9)$$

Where:

C_{pc} = processing cost per component, £

T_{su} = set-up time, hr

T_{cy} = machine cycle time, hr

N_{bs} = batch size,

R_{op} = operation rate, £/hr

y = production yield (<1)

n = number of cavities.

The required machining cost of a moulded component can be computed from the following equation (Shing (1999)). This shows the three elements in the cost of a moulded component.

$$C_{pp} = \frac{C_{mc}}{V_{ol}} + C_{mt} + C_{pc} \qquad (4.\ 10)$$

Where:

C_{pp} = injection moulding component cost,

C_{mc} = total mould manufacturing cost,

C_{mt} = material cost per component,

C_{pc} = processing cost per component,

V_{ol} = production volume of the component.

4.6.3 Cost Analysis Scenario of Moulded Components

The system scenario for injection moulding product cost estimation is described next and shown in Figure (4.12). The system prompts the user to select the manufacturing process for the component. These include machining, injection moulding, casting, sheet metal forming and powder metallurgy processes. The user interacts with the CAD system in the design of the component. Then, the system retrieves the geometric data and volume of the component from the CAD database. The next step is the material selection, discussed in details in the section (4.3.1.5). The material cost is estimated for the candidate material.

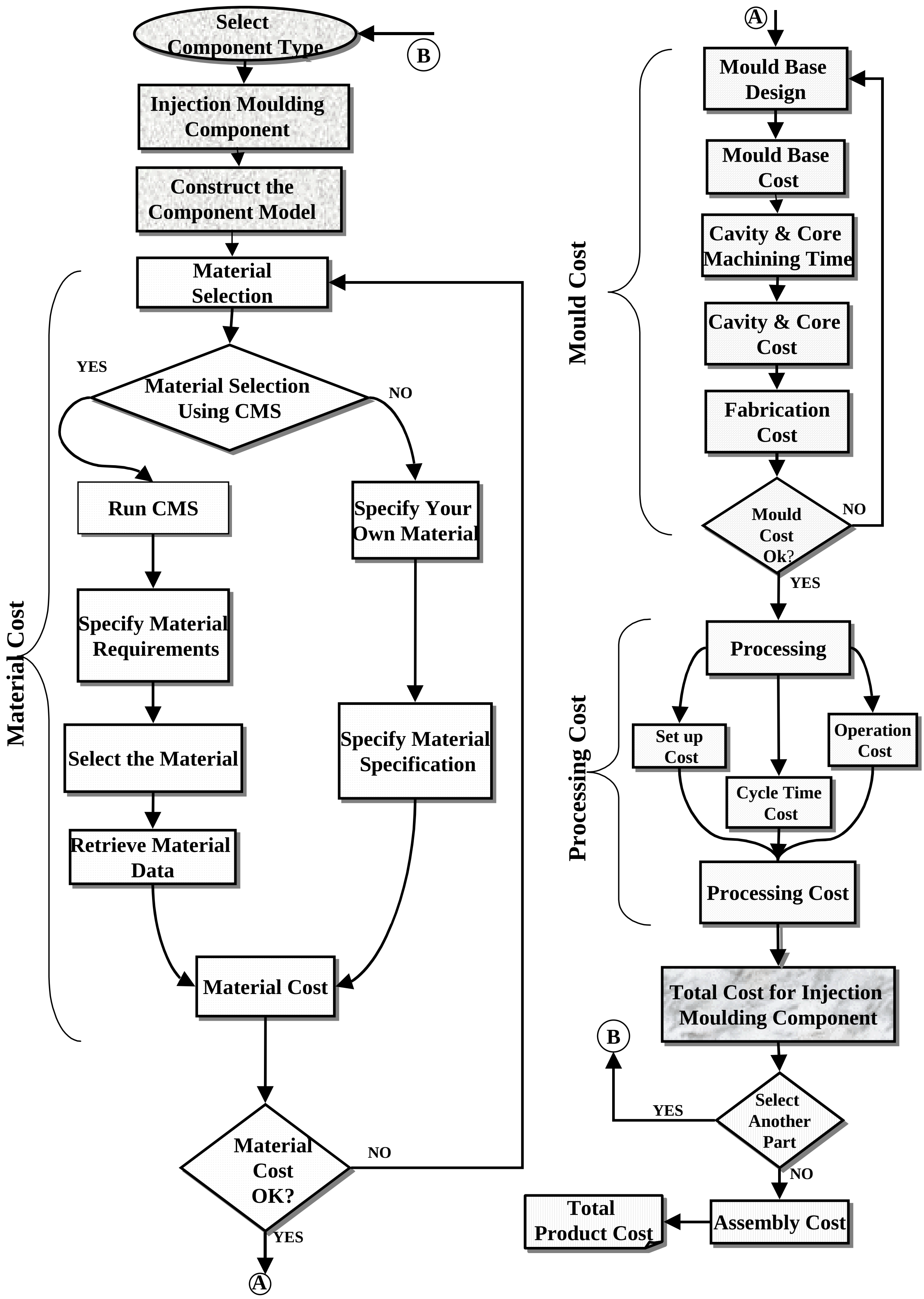


Figure (4.12) Cost Estimation Model of an Injection Moulded Component

The system prompts the user for the number of cavities in the mould. Based on the component data and the number of cavities, the system determines the envelope dimension of the mould base and its cost. The processing cost consists of set-up cost, operation cost and machine cycle time. Based on the operation parameters such as number of operator per machine, number of working shifts, and annual operator cost, the operation cost is estimated. The processing cycle cost time usually includes machine opening and closing times, the injection or filling time, and the cooling time. Finally, a summary of manufacturing time and cost is displayed for the user in a well-designed report.

4.7 Conclusions

An intelligent knowledge based cost modelling system for innovative product development has been described in details in this chapter. In addition, a fuzzy logic model for cost estimation is presented. Two manufacturing processes, namely machining and injection moulding processes were taken into consideration in this research. The developed system presented in this chapter, meets the objectives set out in Section 1.5 by containing the following valuable features:

- The use of the feature-based modelling (FBM) technique for modelling and representing components and their features to provide effective communication within the design team and simplify process planning by the consideration of available processes for components. The CAD solid modelling system, AutoCAD used to generate 3-D models of the intended component, to retrieve topological and geometrical attributes for carrying out the design analysis for manufacturability and cost estimation tasks.

- The system accomplishes an environment that assists inexperienced users to estimate the product manufacturing cost for both machining processes and the injection moulding process.

- In order to generate accurate cost estimates for new designs and explore alternative materials and processes, a combination of cost modelling techniques including heuristics data, algorithmic approach, and a fuzzy logic model, were implemented.

- One of the advantage features of this system is that it warns users of features that are costly and difficult to manufacture. Therefore, designers can modify the product design at any stage of the system running to reach the target cost.

- The system also allows the user to choose between two options: firstly specify the material based on his own criteria. Secondly, It runs Cambridge Material Selector (CMS) software and retrieves automatically the necessary properties for the candidate material.

- The system has the capability to generate initial process planning includes generation and selection of machining processes, their sequence and their machining parameters. The machining parameters comprise of cutting tool type and cutting conditions (e.g. feed rate and cutting speed).

- The proposed system is applied without the need for detailed design information, so that it can be used at an early design stage and consequently redesign cost and longer lead-time can be avoided.

- Efficient representation of cost, manufacturing, and design knowledge by the use of various knowledge representation approaches such as OOP, production rules, and frames to provide flexible, updateable and effective organisation of the knowledge necessary for cost analyses is also provided.

- Normally, the designer would like to see the relation between costs and aspects of the design that he/she can influence directly. A potential solution is to try to specify costs per design feature. Therefore, the system was designed to generate feature-by-feature as well as total product cost estimation report in order to highlight the features of high manufacturing cost. The cost estimation report can be saved as well as printed out for the user

- As the system is knowledge-based, this makes the system flexible and allows users to customise the knowledge stored in the knowledge bases in order to meet the requirements of individual companies.

- A user-friendly interface, which consists of menus, active images and buttons, has been developed for providing the designers with easily input data to the system and complete results of the analysis.

As a result, the developed prototype system has the combination of the above unique features that have not been addressed previously by other systems. These features provide a cost modelling approach that supports concurrent product development.

CHAPTER 5

5 PRODUCT ASSEMBLY COST ESTIMATION AND DESIGN FOR AUTOMATION

5.1 Overview

This chapter proposes a knowledge-based model for product assembly cost and design for automated assembly. The proposed methodology encompasses a knowledge-based system, user interface, a CAD System, a design analysis for automation module and a design improvement suggestion module. The present work focuses upon design feasibility and improvement of a product design for automation / robotic assembly. The steps for functional analysis of a design are also discussed. The various categories of assembly techniques and the criteria to select the most economically assembly technique are described. In addition, cost estimation procedures for manual, automatic and robotic assembly are presented.

5.2 Introduction

Concurrent engineering is a product development philosophy rather than a technology. As mentioned earlier, the major concept of concurrent engineering (CE) is to put the majority of effort in the product design stage to analyse the factors, which might affect subsequent production process. One of the targets of CE philosophy is to reduce both cost and time of a product through simultaneous consideration of product development activities.

Research results show that over 70% of the production cost of a product are determined during the conceptual design stage (Shehab and Abdalla (2001a) and Asiedu and Gu (1998)). Assembly cost often accounts for over 40% of the manufacturing cost (Li and Hwang (1992), and Venkatachalam et al (1993)). Therefore, it is essential to take into consideration the requirements for assembly during the early design stages. Otherwise, cost and time-consuming in redesigning of already finished designs is inevitable.

Design for Assembly (DFA) is a technique for designing products with ease of assembly in mind. A signification reduction in assembly costs can be provided by Design for Assembly (DFA) analysis. In addition, DFA analysis often leads to reduction in overall manufacturing costs that is significantly greater than the reduction in assembly costs. Normally designers are not experts in DFA, so they need a tool that supports them during the design process. In general, approaches to the design of components for assembly are divided into two major categories, design for manual and design for automated assembly.

The relationships between the assembly variables, which play a role in each stage of the design process, is illustrated in Figure (5.1). A certain coherence exists between these assembly variables. When one or more of these variables change, the other variables also have to change. The variables are subdivided into, product, assembly process, and assembly system (Rampersad (1995)).

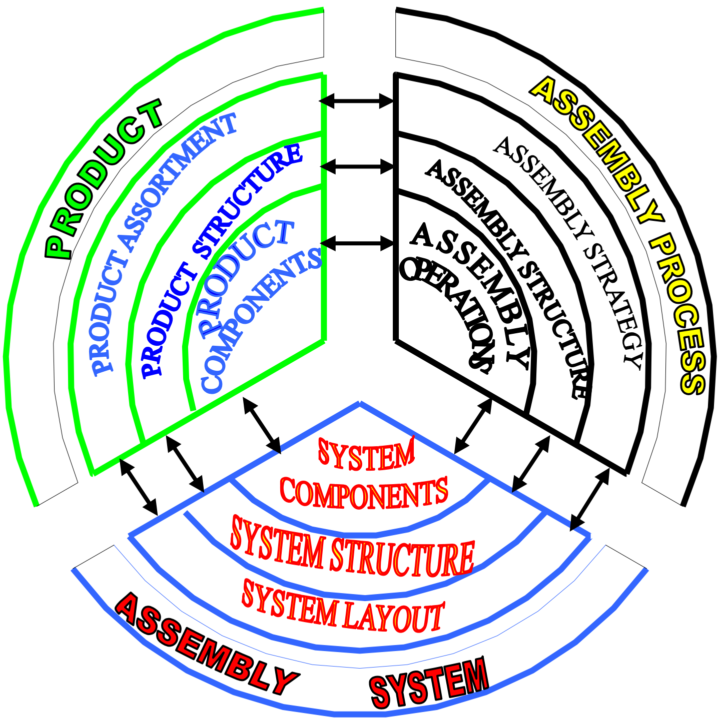


Figure (5.1) The Three Assembly Elements for a Product, (Rampersad, 1995)

The following is a summary of the assembly variables and the accompanying elements:

(i) Product:

- *Product assortment:* the product variants to be assembled.
- *Product structure:* the classification of the product in subassemblies and components, as well as the representation of the relationships between them. On this level there is a strong interaction between the build up of the product, the assembly sequence and the manner in which the various system components are related to one another.
- *Product components:* components of a (sub) assembly or a product. On this lowest level there is a strong relationship between the component characteristics, the complexity of the assembly operations and the properties of the system components.

(ii) Assembly Process:

- *Assembly strategy:* the choices, which are made from alternative methods on a high level of abstraction to increase the controllability of the assembly process.
- *Assembly structure:* the sequence of the relationships between assembly operations.
- *Assembly operations:* feeding, handling, composing, checking, adjusting, and special processes.

(iii) Assembly system:

- *System layout*: an arranged positioning of system components in the space within the assembly system. The system layout results from the system structure.

- *System structure*: a collection of system components, which are mutually related to one another. The location of the system components is determined globally for this purpose.
- *System components*: the subsystems of the assembly system which fulfil functions in the system

It is important to have a measure of how efficient the design is in terms of assembly. The first stage in DFA analysis is to select the appropriate assembly technique for a given product. The product should be analysed for ease of assembly using a particular assembly method selected. The final stage is to improve the design in order to reduce the assembly cost. These stages in design for assembly analysis are shown in Figure (5.2). The most important step of design analysis is functional requirement of a design. The steps of functional design analysis are discussed in the following section.

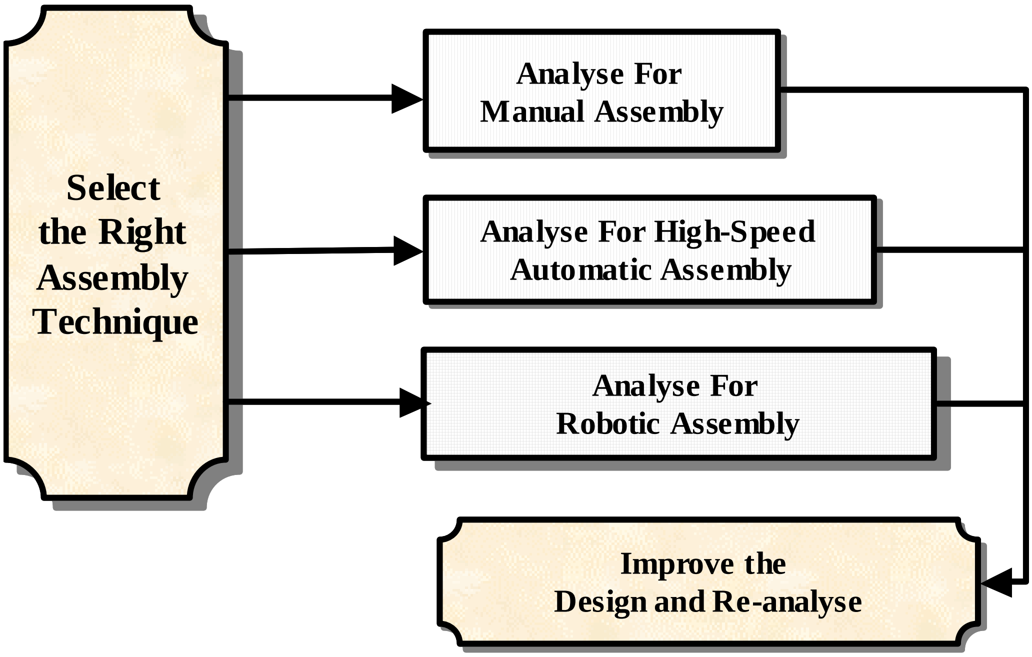


Figure (5.2) Stages in Design for Assembly Analysis

5.3 Functional Design Analysis

The first step of Design for Assembly (DFA) is the functional requirement analysis of a design. The functional analysis is carried out in *FOUR* steps:

Step 1: Determination of the functional requirements of the product.

Step 2: Decide whether the product can be considered as a whole or as a series of functional sub-sections. It is best if possible to consider the product as a whole to avoid the duplication of components or features, which may be in adjacent sub-sections.

Step 3: Components are divided into two categories:

- Essential (Ess) Components: These carry out functions vital to the performance of the product.
- Not Essential (NotEss) Components: Their purpose is not critical to the product function. These may include such item, as fasteners or locators.

Selection of a major functional element is the starting point of the analysis.

Step 4: The mating components are placed into categories in a logical progression using the following questions:

- During the operation of the product, does the component move relative to all other components already assembled?
- Must the component be produced from a different material or be isolated from all other components already assembled?
- Must the component be separate from all other components already assembled because otherwise necessary assembly or disassembly of other separate components would be impossible?

If the answer to any of these questions is yes then the component is essential for the product.

The objective of this analysis is to determine those components necessary for the product (Category Ess) and to highlight the theoretically non-essential ones (NotEss) (Lucas Engineering, 1992).

The influence on the cost of small components is particularly evident in automatic assembly, because each component, in the product, requires a feeding and orienting device, a workhead, at least one extra work carrier, a transfer device and an increase in size of the basic machine structure. Therefore, estimating the theoretical minimum number of components is a particularly important step in the analysis. When the criteria of Functional Analysis has been applied to all components. Then the sum of the essential components is the theoretical minimum number for the assembly. The criteria should be applied without regard to the apparent feasibility of eliminating components or combining them with others. Feasibility and practicality are matters to be addressed by the designer after the analysis.

The basic assembly techniques may be specified as manual assembly, dedicated automatic assembly (special-purpose transfer machine assembly), and flexible assembly (programmable robot assembly). These assembly techniques are presented in the following section.

5.4 Classification of Assembly Systems

The cost of assembling a product is related to both the design of the product and the assembly method used for its production. The lowest assembly cost can be achieved by designing the product so that it can be economically assembled by the most appropriate assembly method. There are three basic assembly techniques and these are:

- **Manual assembly**

- MA - Manual Assembly

To represent manual assembly systems, it will be assumed that the assembly process is broken down into individual tasks and performed in sequence by a series of operators arranged in 'assembly-line' fashion. An individual operator will continually repeat the same operation or limited series of operations and the rate of output from the line will be dependent on the time taken by the slowest operator.

One advantage of this scheme, compared to a multi-station assembly machine, is that by providing each operator with more than one assembly task (several components assembled at each station) and the output from the assembly line can be matched more closely to the production rate required. Another advantage is that an operator can quickly recognise a defective component and discard it with a little loss to production (See Figure (5.3)).

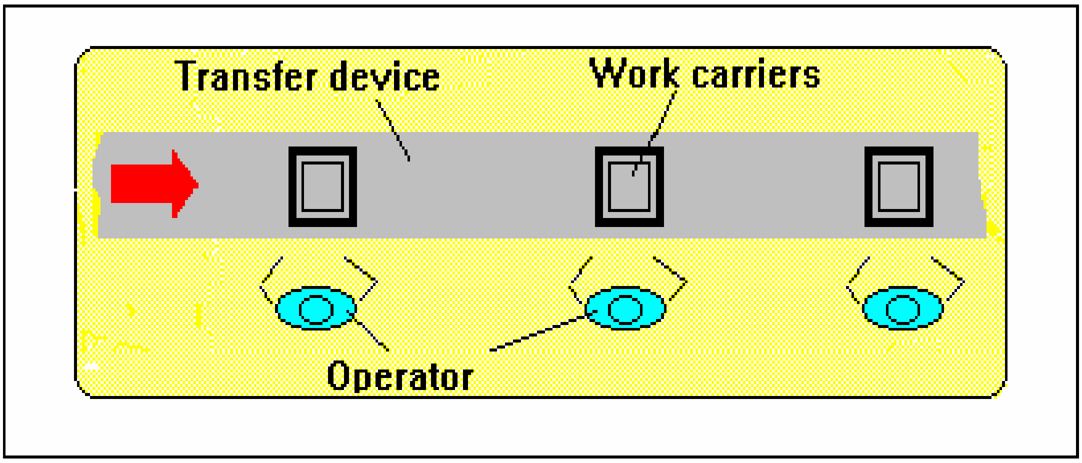


Figure (5.3) Manual Assembly (MA)
(Daabub, 1999)

- MM - Manual Assembly with Mechanical Assistance

In some situations, it was found that assembly times can be reduced by providing the operators with mechanical assistance; for example by providing oriented components from automatic feeding and orienting devices (See Figure (5.4)).

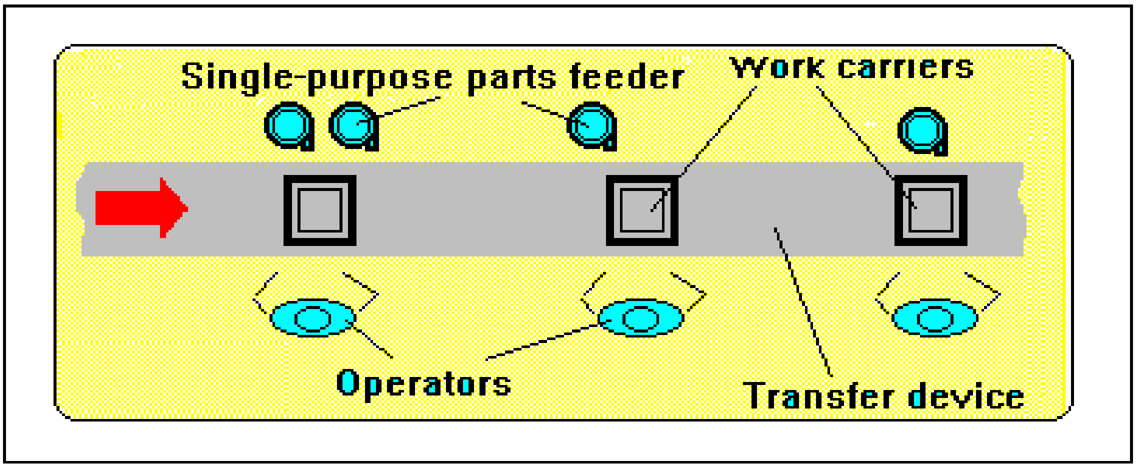


Figure (5.4) Manual Assembly with Mechanical Assistance (MM),
(Daabub, 1999)

- **Special-purpose transfer machine assembly**
- Special-Purpose Automatic Assembly using indexing machines (AI)

Assemblies are transferred by an indexing transfer device (rotary or in-line). In assembly systems, using special-purpose machinery, the various individual assembly operations are generally carried out on separate workstations. For this type of assembly, the partially completed assemblies are transferred automatically from workstation to workstation. A means is provided of ensuring that no relative motion exists between the assembly and the work-head, while the operation is being carried out.

As the assembly passes from one station to another, it is important to be maintained in the required attitude. For this purpose, the assembly is usually built up on a base or "work carrier" and the machine is designed to transfer the work carrier from one station to another.

Assembly machines are usually classified according to the system adopted for transferring the work carrier. Thus an "in-line" assembly machine is one where the work carriers are transferred along a straight slide way and a “rotary” machine is one where the work carriers move in a circular path. Also, those assembly machines, which transfer all the work carriers simultaneously, are known as “indexing” machines and on these machines a stoppage of any individual work-head causes the whole machine to stop.

With a rotary indexing machine, indexing of the rotary table brings the work carriers under the various work-heads in order to carry out the insertion operation. Thus, at the appropriate station, a completed product may be taken from the machine after each indexing operation.

The in-line-indexing machine works on a similar principle but in this case a completed product is removed from the end of the line after each index. With in-line machines, provision must be made for returning the empty work carriers to the beginning of the line.

Again one basic characteristic, which is common to all indexing machines, is that a breakdown of any individual workstation will stop the whole machine and production will cease until the fault has been cleared (See Figure (5.5)).

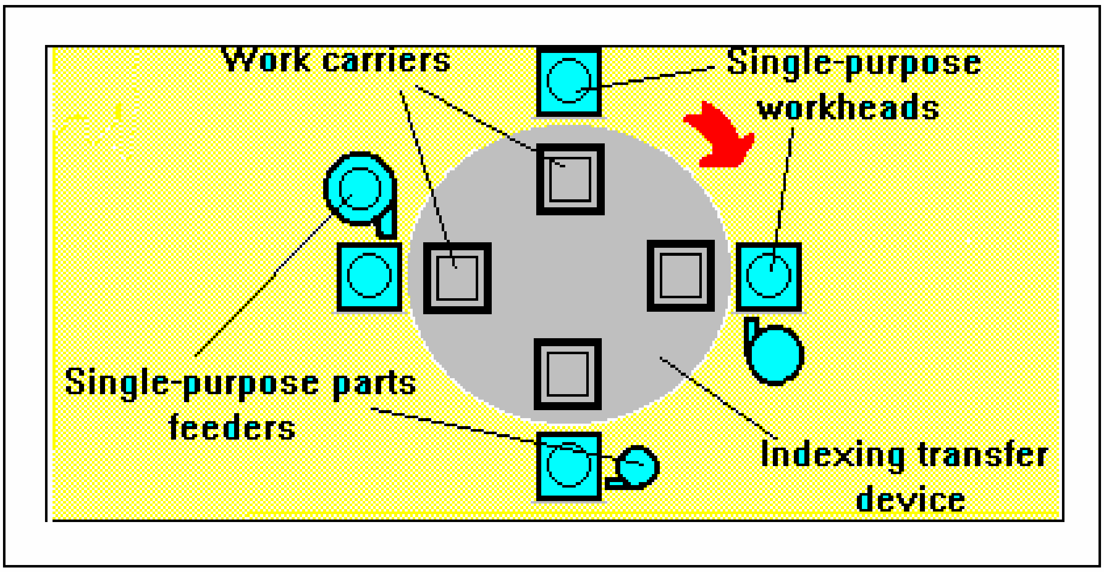


Figure (5.5) AI Drawing

(Daabub, 1999)

- **Automatic assembly using free transfer machines (AF)**

One type of in-line machine is known as a free-transfer machine. Here the spacing of assemblies can accumulate between adjacent stations. Each workstation or operator works independently and the assembly process is initiated by the arrival of a work carrier at the station.

The first operation is to lift the work carrier clear of the continuously moving conveyor and clamp it in position. After the assembly operation has been completed, the work carrier is released and transferred to the next station by the conveyor, provided that a vacant space is available. Thus, on a free-transfer machine a fault at any one station will not necessarily prevent the other stations from working. It will now be shown that this is an important factor when considering the relative economics of indexing and free-transfer machines (See Figure (5.6)).

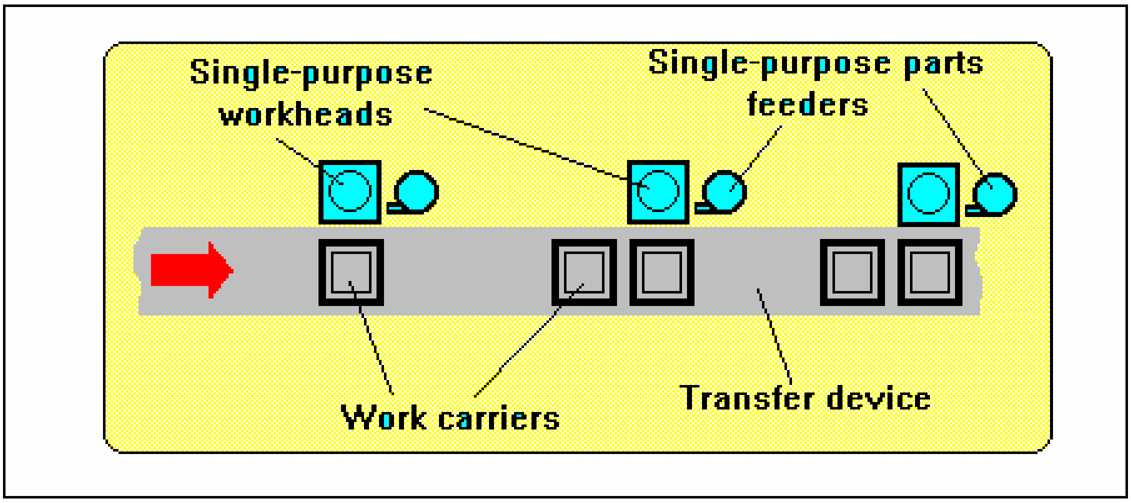


Figure (5.6) Automatic Assembly using Free Transfer Machines (AF) (Daabub, 1999)

- **Automatic Assembly with Programmable (AP)**

These machines are basically special-purpose machines, where the single task workstations are replaced by programmable workstations capable of performing more than one assembly task. This scheme provides flexibility in that the machine can be designed to match more closely the annual production volume required. In addition, product style changes can be accommodated since the workstations are under computer control and can be commanded to select components among alternatives available at a particular station (See Figure (5.7)).

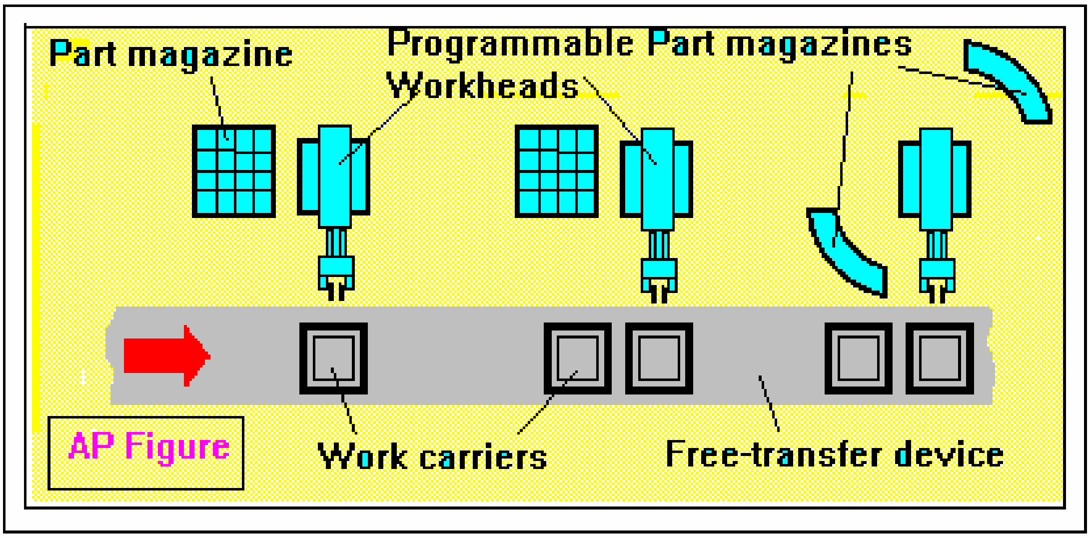


Figure (5.7) Automatic Assembly with Programmable (AP)

(Daabub, 1999)

- **Robot assembly (AR)**

Robotic assembly has many advantages, such as stability of product design, reducing product costs, accommodation of product style variations and no restrictions on component size if the component can be presented in pallets or component trays. The various robotic assembly systems are categorised as follows:

- Single station with one arm robot assembly system,
- Single station with two-arm robot assembly system (See Figure (5.8)),
- Multi-station robot assembly system.

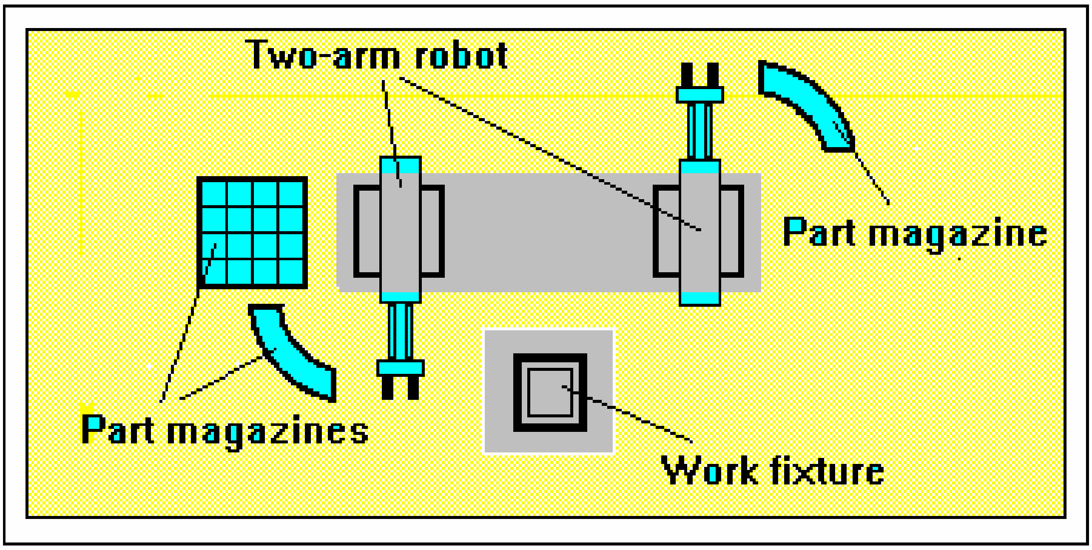


Figure (5.8) Robotic Assembly (AR)

(Daabub, 1999)

In practice, assembly systems can be a combination of one or more of these methods. Each of these techniques has its appropriate range of conditions for economic application, depending on the number of components to be assembled, the production volume, etc. Figure (5.9) illustrates these three assembly methods in relation to production volume, product variety, batch size and flexibility.

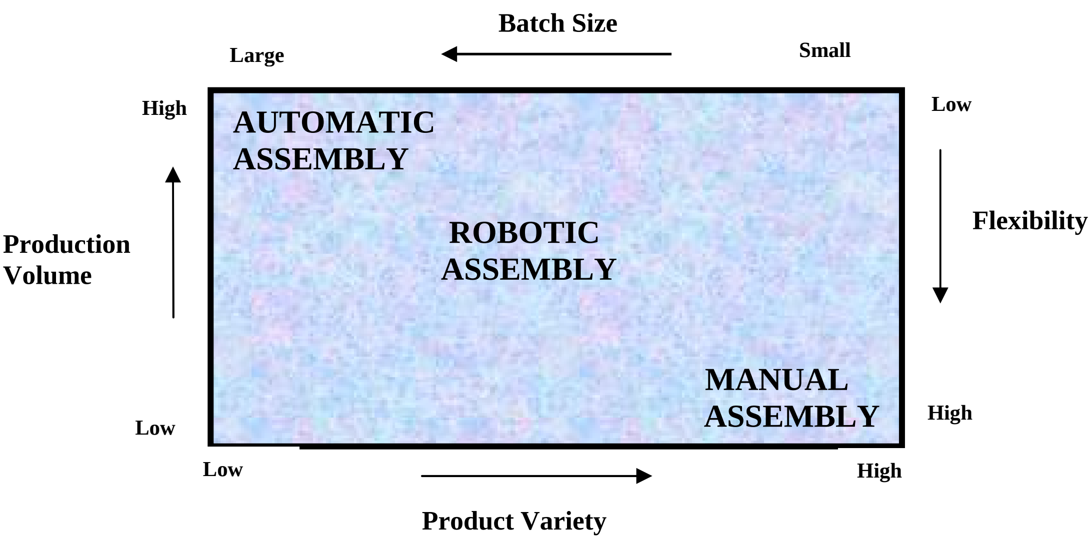


Figure (5.9) Assembly Methods related to Production Parameters

5.5 The Proposed Approach to Design for Assembly

The system framework for design for assembly comprises of a knowledge-based system, CAD System, design analysis for robotic assembly module, design improvement suggestion module and user interface The basic architecture of the system model is illustrated in Figure (5.10). The developed system was designed in such a way in order to allow designers to analyse and/or modify the product at any stage of design process. It works in a full interactive mode.

The designer communicates with each module via the user interface. He/she has to specify, to the system, the basic product specifications and the production data such as production volume, number of components and number of working shifts. These data are employed in the system to select the most economic assembly technique for the product. The system then commences the design analysis for the selected assembly method. The system presents the design analysis in an efficient user interface.

Normally designers are not expert in DFA especially robotic assembly. Therefore, they need a tool that supports them during the design process. The design for automation module has the capability to apply the design criteria for robotic assembly. The roles of design improvement module are to:

- Identify automatically the candidate component(s) for redesign,
- Specify the various component features that cannot be assembled robotically,
- Provide possible alternative redesign suggestions.

Discussion of each module is presented in the following sections.

5.5.1 Design for Assembly Knowledge Representation Techniques

Knowledge representation is the formal description of the knowledge with symbolic encoding. It deals with how to organise and encode knowledge in the best form so that the problem can be easily solved. In the domain of DFA, the knowledge-based contains knowledge that provide assembly selection, assembly time and cost estimation, design analysis and redesign suggestions heuristics.

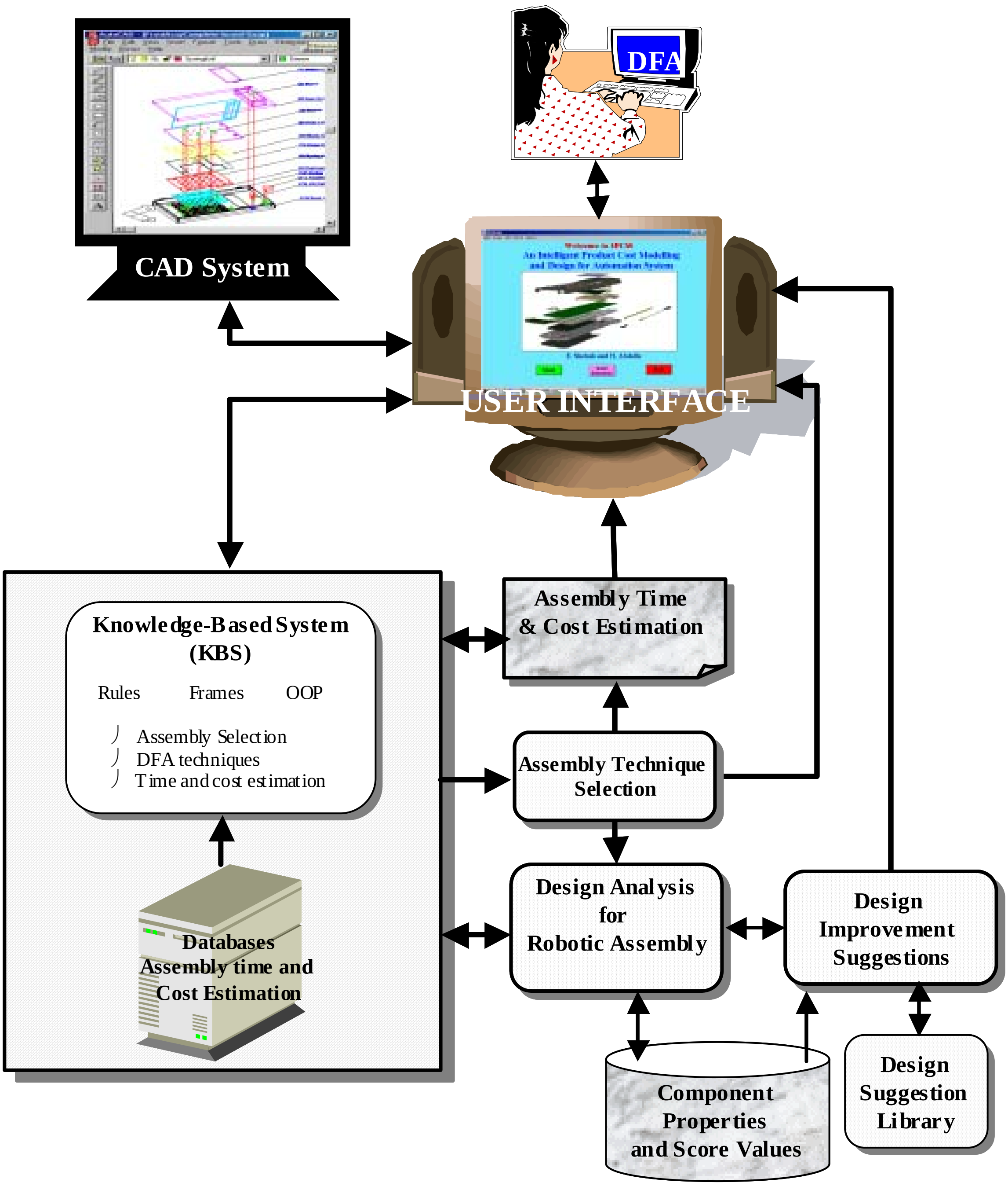


Figure (5.10) The Structure of Design for Assembly Module

In this study, open literature as well as interviews with manufacturing experts in selected companies are the main sources of the knowledge used in building the knowledge-based for assembly analysis and evaluation. Hybrid knowledge representation techniques are employed to represent knowledge-based of component feeding, handling and insertion in this research. These techniques, such as production rules, frame and object oriented are described in detail as follows.

5.5.1.1 Production Rules

The knowledge of assembly design can be represented as a production rule in the form **IF** premises **Then** conclusion. The rules are connected to each other so that the conclusion of one rule is included in the premise of another rule. This technique is called chaining. When chaining commences, conclusions of one rule class match the premises of another rule class. Chaining is used either in a forward or backward direction. The following are examples of interrelating rules used in the system to estimate the manual handling and insertion time ((MHT) and (MIT)).

MHT_Rule_1

IF	*(The component manipulated by one hand)*	*AND*
	(Tools are required to manipulate the component)	*AND*
	(The required tools are tweezers)	*AND*
	(Optical magnification is not required)	*AND*
	(The component is easy to grasp)	*AND*
	(Thickness is greater than 0.25 mm)	*AND*
	(The degree of alpha symmetric (α) is equal to 360°)	*AND*
	(The degree of beta symmetric (β) is less than 180°)	

THEN *(the manual handling time is equal to 4.8 seconds)*

MIT_Rule_1

IF	*(The component is not secured immediately after insertion)*	*AND*
	(The component is not easy to reach desired location)	*AND*
	(There is obstructed access and restricted vision)	*AND*

(The component required holding down after insertion)   AND

(The component is easy to align)   AND

(The component required resistance to insertion)

THEN *(The manual insertion time is equal to 10.5 seconds)*

5.5.1.2 Frame-Based Knowledge Representation

A frame is a data structure for storing interconnected information about a design and an object. It is a very effective means of providing knowledge representation of stereotypical objects. The frame consists of a name and a number of slots. A slot consists of multiple sides, and a side consists of multiple values. Frame, slot and side can describe various kinds of information. The frame system offers both inheritance and exception handling properties. The former allows a slot to inherit the properties of its parent slot, while the latter is achieved via conditional slots (consisting of "if-then" rules) associated with each frame. The frames in Kappa-PC expert system toolkit, developed by Intellicorp, are very flexible so that images and active values can be attached to any slots to monitor changes in value. An example of frame representation of an object is shown in Figure (5.11).

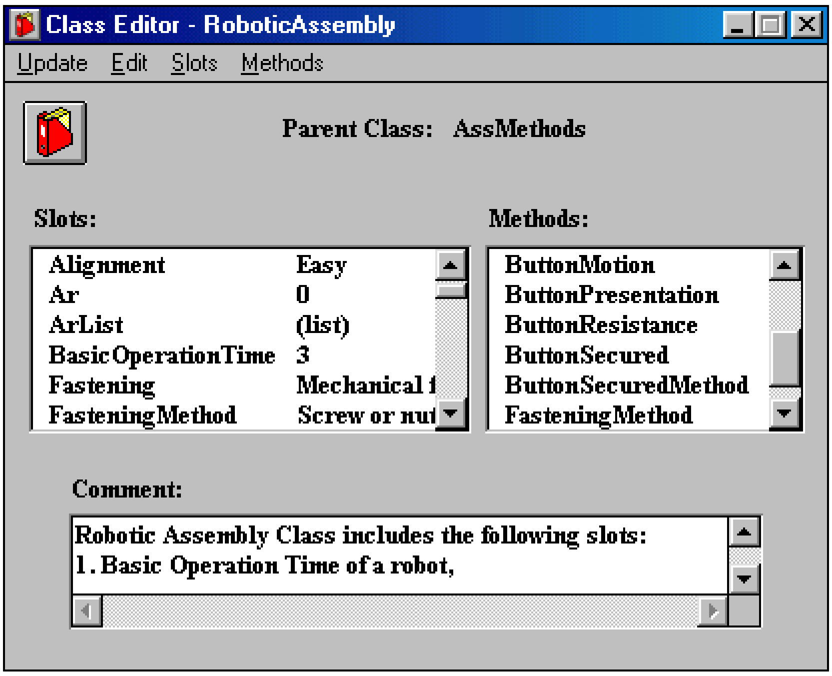


Figure (5.11) Frame Representation of an Object

5.5.1.3 Object-Oriented Knowledge Representation

Object-oriented programming systems have an inherent ability that appeals to designers, as they enable designers to model real world design problems as a set of objects. Thus, they provide designers with an expressive power to represent complex problems or information in an effective manner. Using such a technique, design, manufacturing, and assembly techniques, such as manual assembly, automatic assembly and robotic assembly can be organised into various classes represented in hierarchies. A class has a name and several subclasses, consisting of a number of objects with a number of slots, attributes such as basic operation time of a robot, fastening method, and feeding technique. All classes can be broken down into subdivisions so that all components of the class are considered. Figure (5.12) shows object-oriented representation of the redesign suggestions and the various assembly methods employed. One of the reasons for using object-oriented technique is to take advantage of its characteristics of data abstraction, inheritance, and modularity. The inheritance property enables the designer to define a specific value into a higher class each can be inherited by the lowest class of the hierarchy.

5.5.2 User Interface

A user-friendly interface has been developed, as an important part of the proposed system, in order to enable the user to use the system easily and efficiently. The Kappa-PC toolkit's features such as sessions, popup windows, menus and images were used to create the user interface so that the user-defined values could be used to accomplish the design for assembly tasks. An example of the developed user interface is shown in Figure (5.13). The design analysis and recommendations for redesign suggestions are displayed on separate screens. The various elements of the product assembly cost are reported to the user in a Kappa-PC window. Graphics were used in the development of the software. Finally the user is provided with options to clear the working memory and restart another application, to make hard copy of the system recommendations and reports, or quit the system altogether.

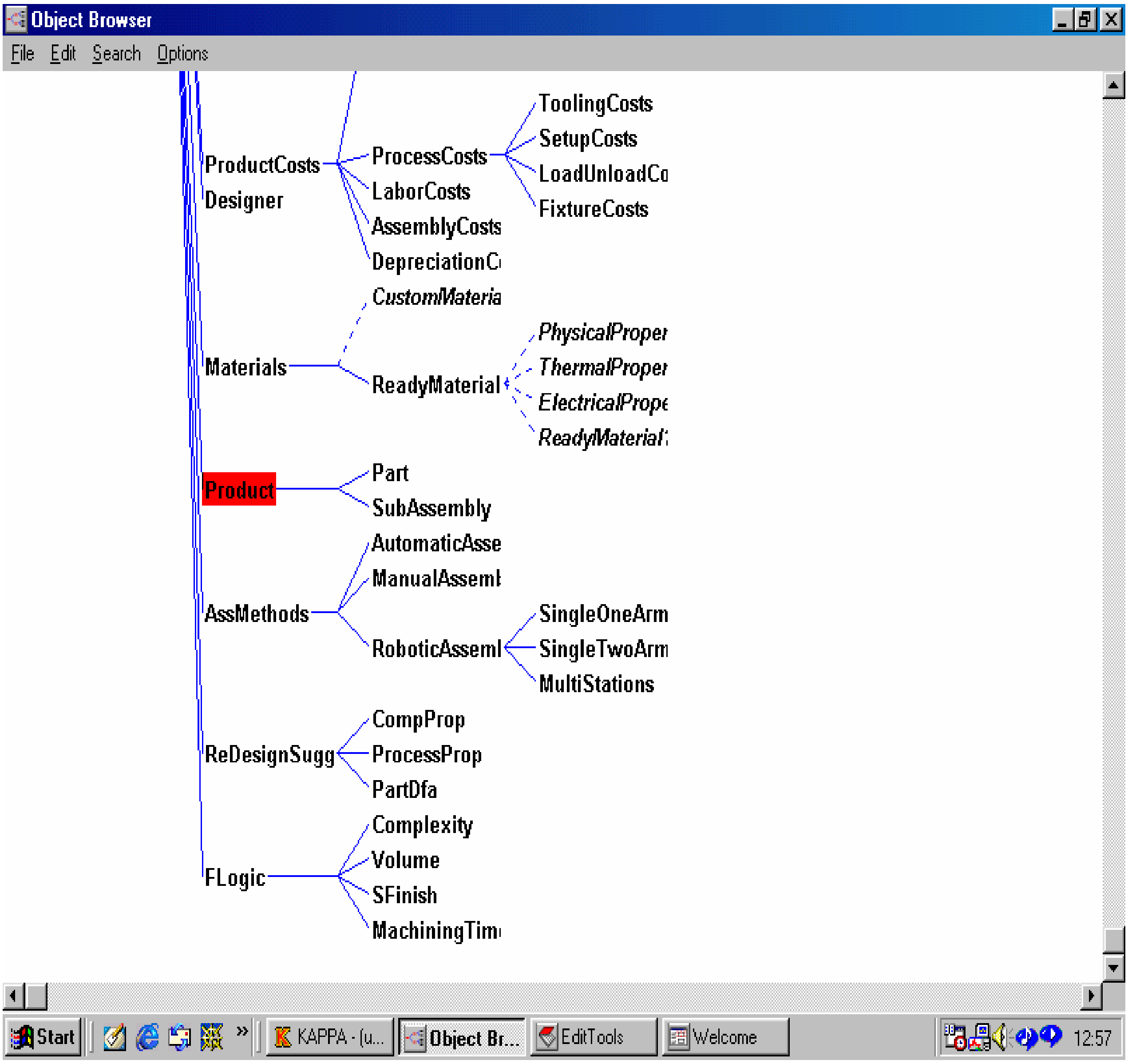


Figure (5.12) Object-Oriented Representation of the Various Class of Assembly Systems and Redesign Suggestions

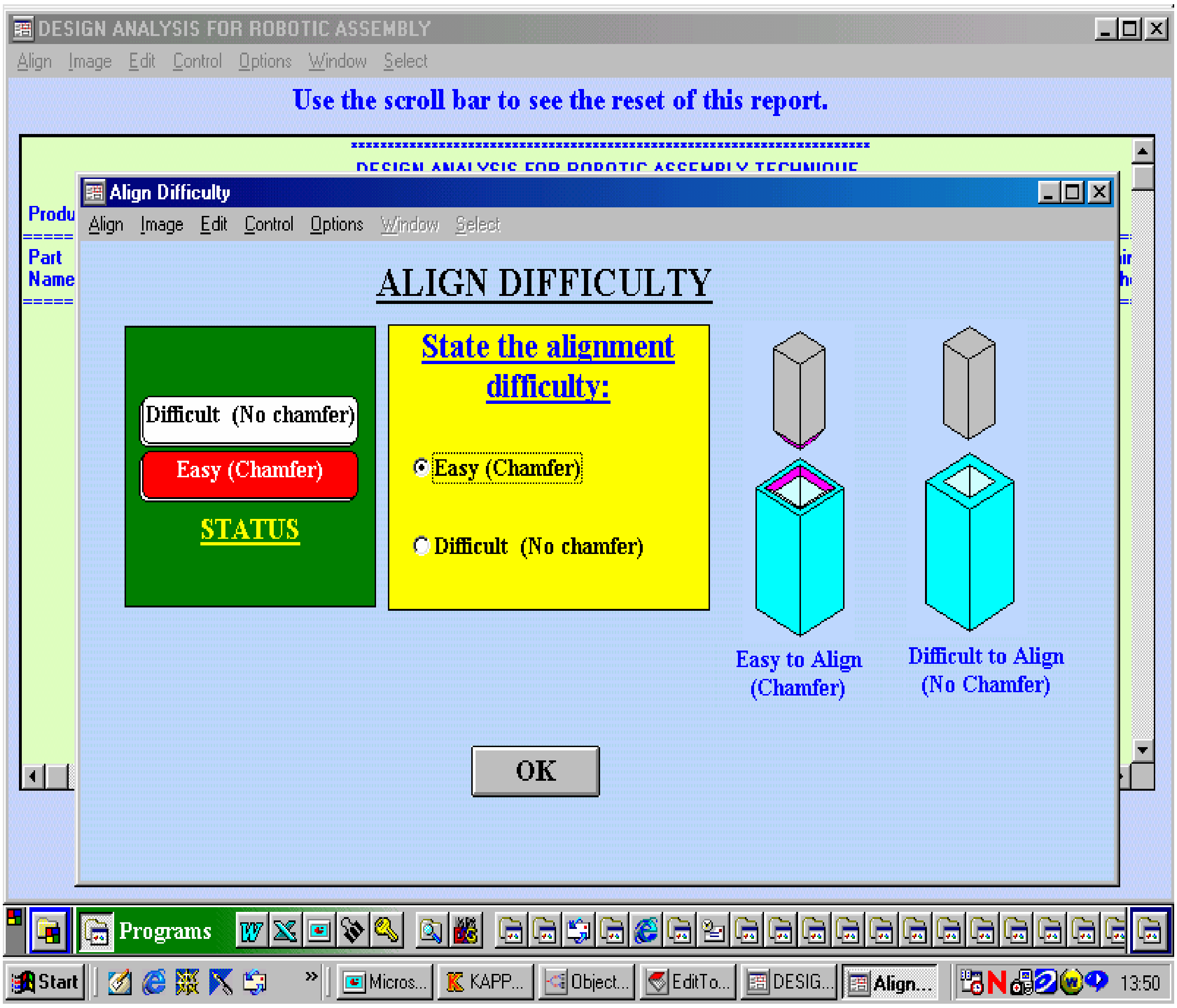


Figure (5.13) An Example of the User Interface Developed in the System

5.5.3 Database

The proposed model for DFA includes four groups of databases: assembly systems, time and costing for assembly methods, assembly properties score values for a specific product, and target score values for the assembly properties. The first group consists of the assembly system selection data, such as assembly system types and their applications. The second group involves data concerning assembly operations, time, and cost. The third group contains the assemblability score values and corresponding properties for the product. The final group includes the target value for each assembly property.

The proposed system operates with two types of database namely, permanent (static) and temporary (dynamic). The permanent database, such as the target score values for various assembly operations, is not altered as a result of using the system over a period of time. On the other hand, the temporary database, such as properties values database is updated as a result of running the system.

5.5.4 Selection of the most Economic Assembly Technique

It is important to decide at an early design stage, which type of assembly method is likely to be adopted. This is based on the method that yields the lowest costs. The reason, that early process selection is important, is that manual assembly differs widely from automatic or robot assembly due to the differences in ability between human operators and any automatic method of assembly. An operation that is easy for an individual person may be impossible for a robot or special -purpose work-head, and to carry out operations that are easy for machines may be difficult for people.

In product development there will be specification of the quality levels of the individual components from the technical requirements for the product. It is necessary that all the quality parameters of a component are specified in relation to the requirements of a product and assembly technology, via close co-operation between product development and methods of planning. Tolerance limitations become necessary with the increasing level of automation of assembly technique.

Fortunately, detailed knowledge of the product design is not required to decide upon the most economic assembly process. Only the basic product specification and the company parameters such as production volume, number of components, and number of working shifts are required at the selection of the assembly method stage.

The cost of assembling a product is related both to its design and the assembly method used for its production. The lowest assembly cost can be achieved by designing the product so that it can be economically assembled using the most appropriate assembly method.

Detailed knowledge of the product design is not required to make a good estimate of the most economic assembly process. What must be known are the projected production volumes and a company's investment policy (see Figure (5.14)). The investment factor (R_i) that one of factors for selection can be calculated using the following formula:

$$R_i = S_n * Q_e / W_a \qquad (5.1)$$

Where

Q_e: Capital expenditure allowance to replace one operator on one shift

S_n : Number of shifts worked

W_a : Annual cost of one assembly operator.

A set of interrelating rules in the system (see an example below) is used to select the right technique.

ASS_Selection_Rule1:

IF *(Product type is single)* *AND*

(Total number of components for different product styles ≥ No. of product components times 1.5) *OR*

(No. of design changes ≥ the No. of Product components) *AND*

(Production volume > 650000) *AND*

(No. of components ≥ 16) *AND*

(Investment factor > 1)

THEN *Automatic assembly using programmable workheads (AP) is most likely to be economic for the particular product*

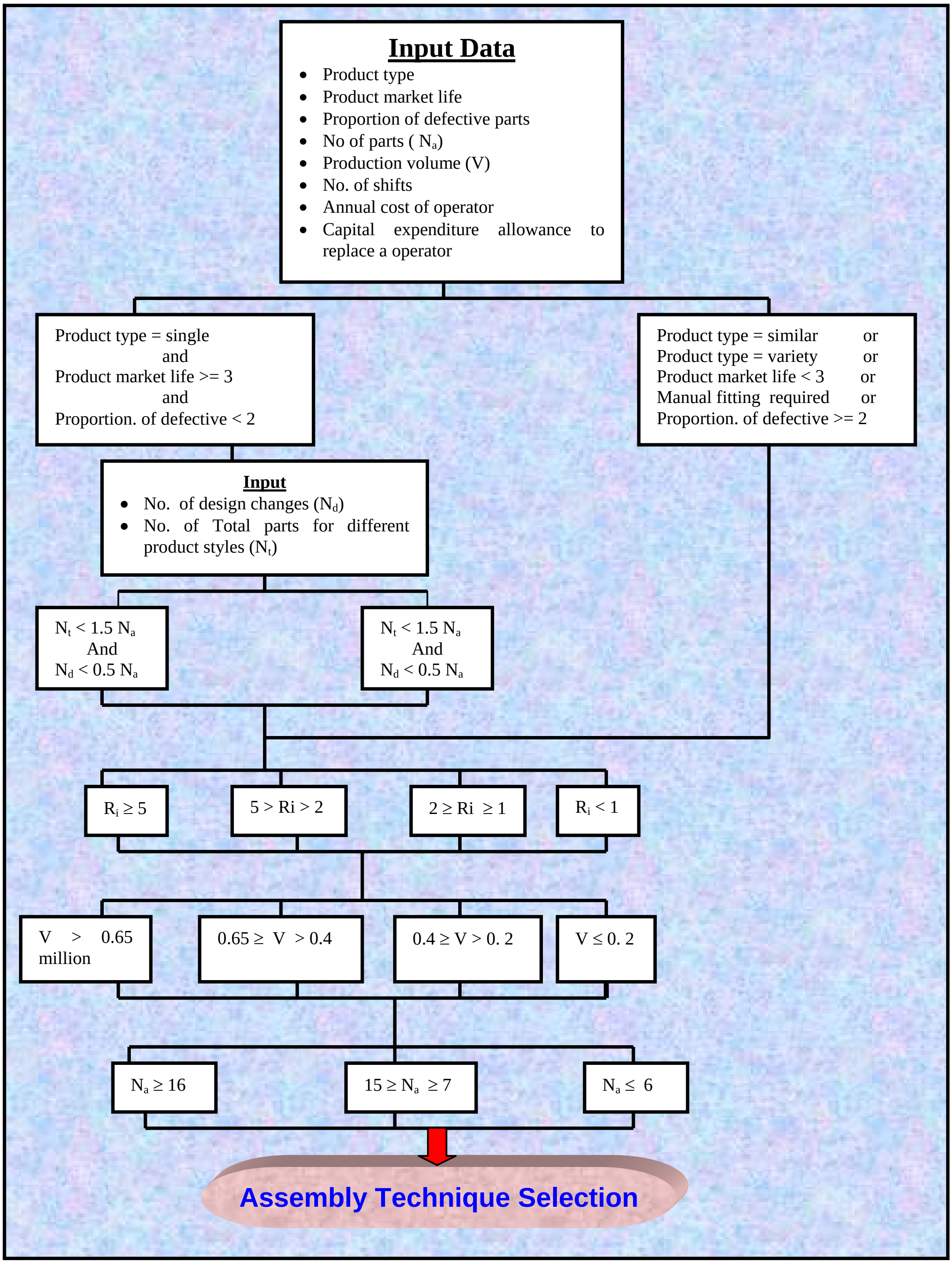


Figure (5.14) Stages of Selecting the most Economic Assembly Technique

5.5.5 Design Analysis for Robotic Assembly Module

As stated earlier the importance of robotic assembly is well recognised, but many designers do not have the necessary knowledge in this assembly technique. This system provides the capability of carrying out design feasibility and obtaining design improvement suggestions for robotic assembly. The first stage in design improvement is to identify the weak points in the product design. The architecture of design analysis for robotic assembly is shown in Figure (5.15). The properties values database is used to store all the assemblability score values and corresponding properties for the product and the score values database saves the target value for each property. The target value is obtained from the objective value and the lowest score of the property. The design criteria for robotic assembly have been applied for each component. The system evaluates, technically the separate subassemblies and components, as well as the whole assembly, for the possibility of robotic assembly. The component and subassembly properties used are stiffness, vulnerable, shape, sizes, symmetry, quality, weight, and joining method (see Figure (5.15)). The assembly properties include the number of components, base component, and product length. The assembly process properties are categorised into, status during feeding, assembly direction, the need to be hold down during insertion, alignment difficulty, resistance to insertion, and the number of motion during insertion. When a criterion is applied for a component, score points are given to the component. A score ranging from 1 to 4 points is awarded to a component, according to the degree of its influence on the complexity of the assembly process. For instance, if a component strongly is fulfilled the vertical composing from above criterion, then a score of 1 point is given to the component. In contrast if another component is assembled from the sides or below. As result, this component is awarded by score of 4 points. The total score of a component is the sum of the scores of each property. A design analysis report is generated for the designer. Attention in the redesign stage for robotic assembly technique focuses upon the relatively highest component scores. The property with the highest score for a component infers that this property is a subject for redesign.

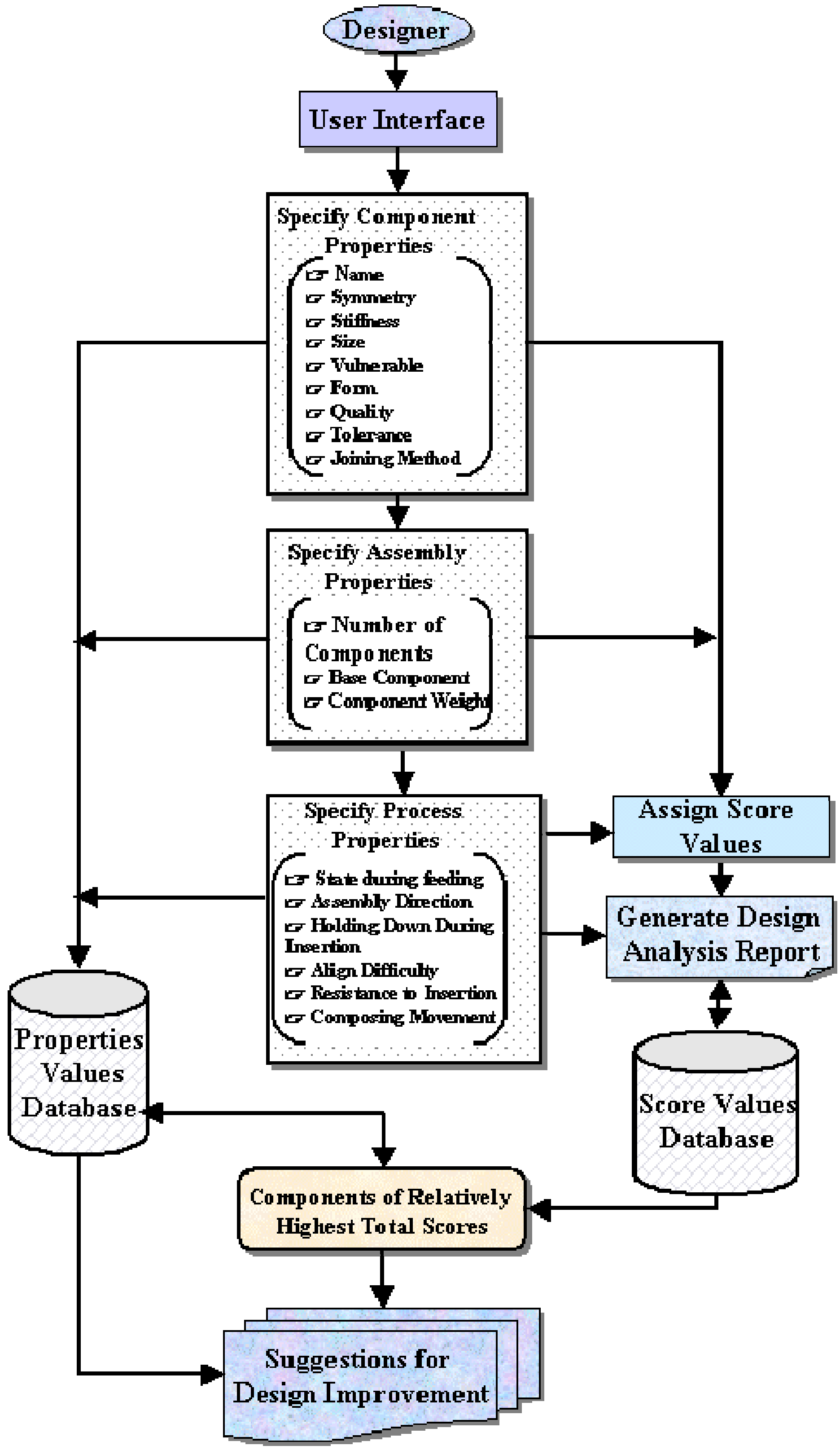


Figure (5.15) The Architecture of Design Analysis for Robotic Assembly

5.5.6 The Design Improvement Module

Redesign suggestions are the most difficult task in the developed system. Practically, a redesign suggestion is heavily dependent on experienced engineers and should be a teamwork task. In order to initiate the suggestions for redesign, the design improvement module performs three functions. Firstly it identifies automatically those components with the highest total scores. Secondly it specifies the component and assembly process properties that are candidates for redesign. Finally it provides suggestions for redesign, which will simplify the task of robotic assembly. The flowchart for the redesign stage is illustrated in Figure (5.16)).

The options for product redesign to simplify the assembly process are set out in Figure (5.17)). These include feeding, handling, and composing processes. Examples of the feeding processes are nesting, overlapping, tangle, and orientation. Handling processes include stiffness, vulnerable, component weight and shape. The composing processes include tolerances, resistance to insertion, assembly direction, composing movement, joining method, and alignment difficulty. A series of design modifications are provided to assist in simplifying the assembly process. The design suggestions are displayed, for the designer, in a professional way. An example of a re-design suggestion is shown in Figure (5.18).

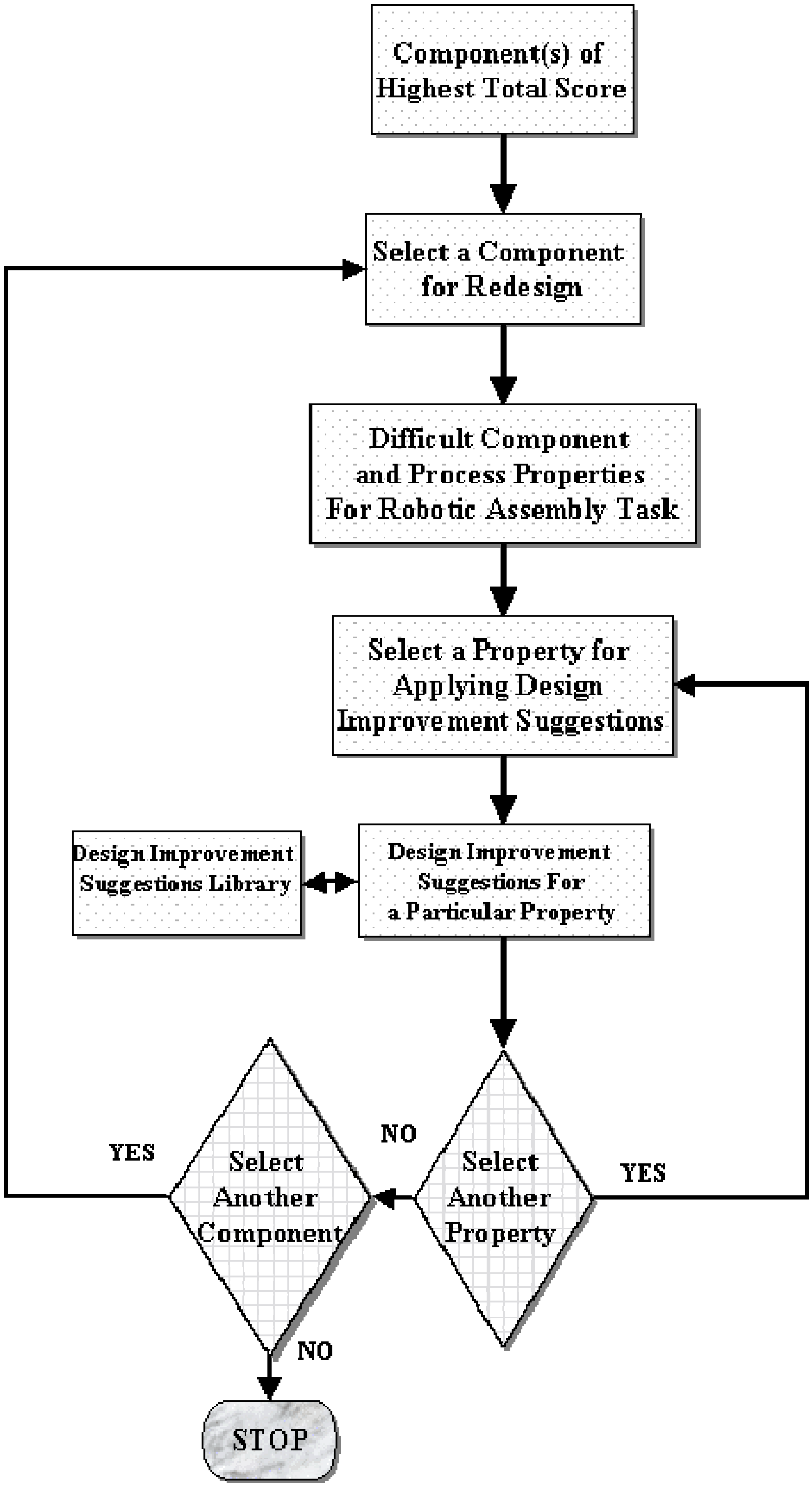


Figure (5.16) The Flow Chart for Redesign Stage

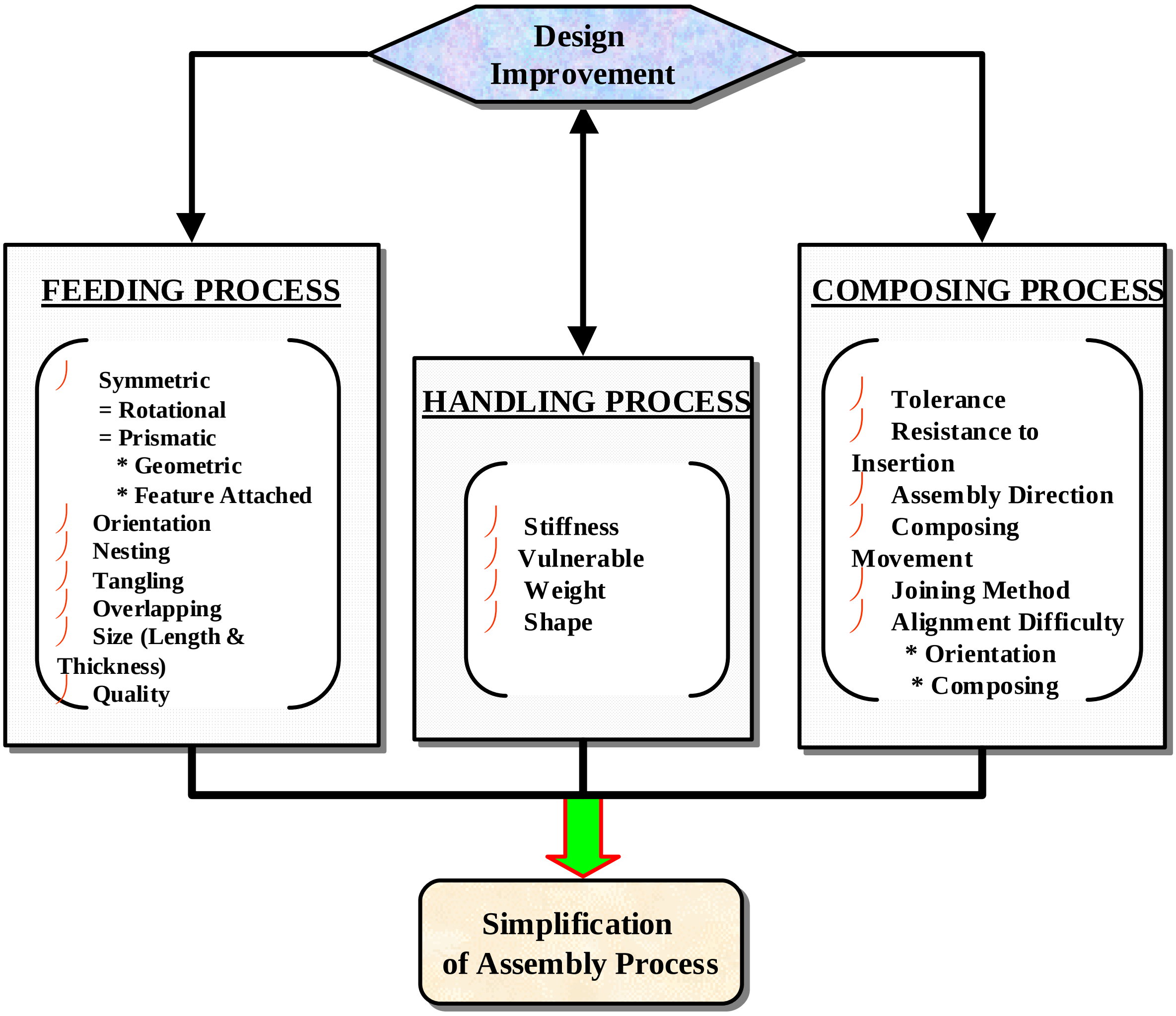


Figure (5.17) The Various Assembly Operations Considered for Redesign

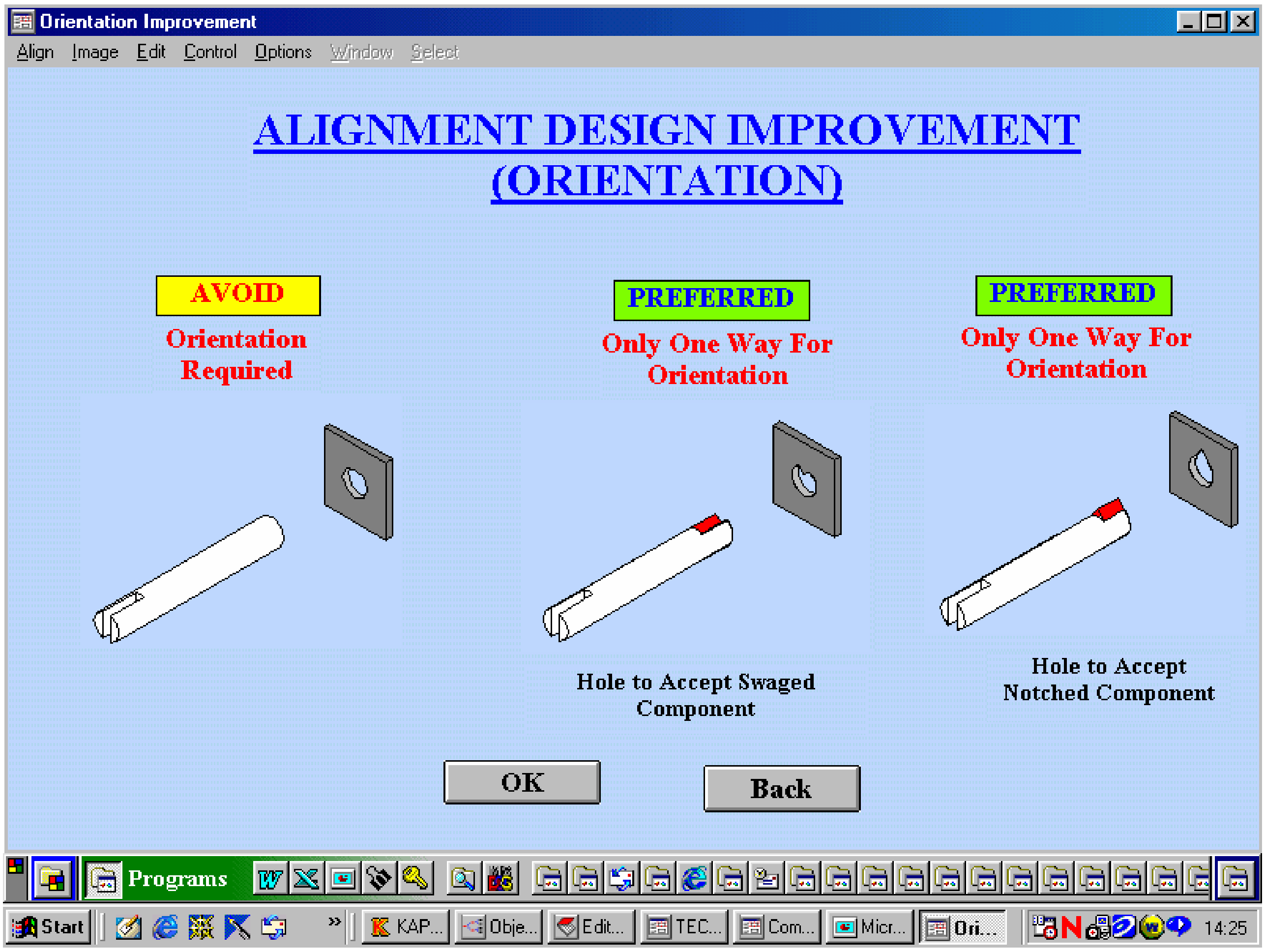


Figure (5.18) An Example of a Re-design Suggestion

5.6 Cost Analysis for Manual Assembly

When it has been decided that the product or assembly is likely to be assembled manually, then the procedures described in this section are used to analyse the design, identify assembly difficulties, and estimate the assembly cost. In this technique, features of the design are examined in a systematic way and at the end of the procedure the assembly cost is estimated and the design efficiency calculated. The design efficiency and cost estimation can be used to compare different designs. The technique involves for each component in assembly, estimation of the time taken to grasp, manipulate and insert the component.

5.6.1 Procedure for Manual Assembly Analysis

This method for analysing the design identifies those features, which result in high assembly costs. In order to calculate manual assembly costs the following steps are considered.

Step 1: Obtain the best information about the product or assembly. This information can be obtained from engineering drawings, exploded three-dimensional views, an existing version of the product or a prototype.

Step 2: Assign an identification number to each component. If the assembly contains sub-assemblies treat these, at first, as "components" and then analyse the sub-assemblies later.

Step 3: This step requires estimation of the Manual Handling Time (MHT). It is estimated automatically by the proposed system. The system analyses the component by asking the user/designer about the component status through a common language, independent of traditional engineering disciplines. A set of interrelating rules, in the system, is then used to estimate the manual handling time (MHT).
The criteria for MHT estimation is based on the features of the component (see

Figure (5.19)) such as whether or not:

- The component needs one hand or two hands for manipulation,
- Tools are required for manipulation,
- The component is easy to grasp,
- The component needs optical magnification for manipulation,
- The component requires additional handling because it nests or tangles.

Also, the designer has to assign the dimensions of the component, and the degrees of alpha symmetric (α) and beta Symmetric (β). The production rules knowledge-based representations are employed to represent the knowledge of manual handling time.

Step 4: After the analysing the component for manual handling and the MHT is estimated, the system starts to analyse the component for manual insertion. Then the Manual Insertion Time (MIT) is estimated automatically by the system. A set of interrelating rules, in the system, is then used to estimate MIT.

The criteria for MIT estimation is based on the assembly features during and after insertion (see Figure (5.20)). This takes into account whether or not:

- The component is secured immediately after insertion,
- The component is easy to reach at the desired location,
- There is obstructed access or restricted vision or both,
- The component requires holding down,
- The component is easy to align,
- The component has resistance to insertion,
- The component needs an assembly operation after insertion e.g. Screwing, riveting, bending, etc.

The following rule is illustrative of the interrelating rules in the system to estimate MIT.

MIT_Rule_1

IF *(The component is not secured immediately after insertion)* *AND*
(The component is not easy to reach at the desired location) *AND*
(There is obstructed access and restricted vision) *AND*
(The component required holding down after insertion) *AND*
(The component is easy to align) *AND*
(The component required resistance to insertion)

THEN *(The manual insertion time is equal 10.5 s)*

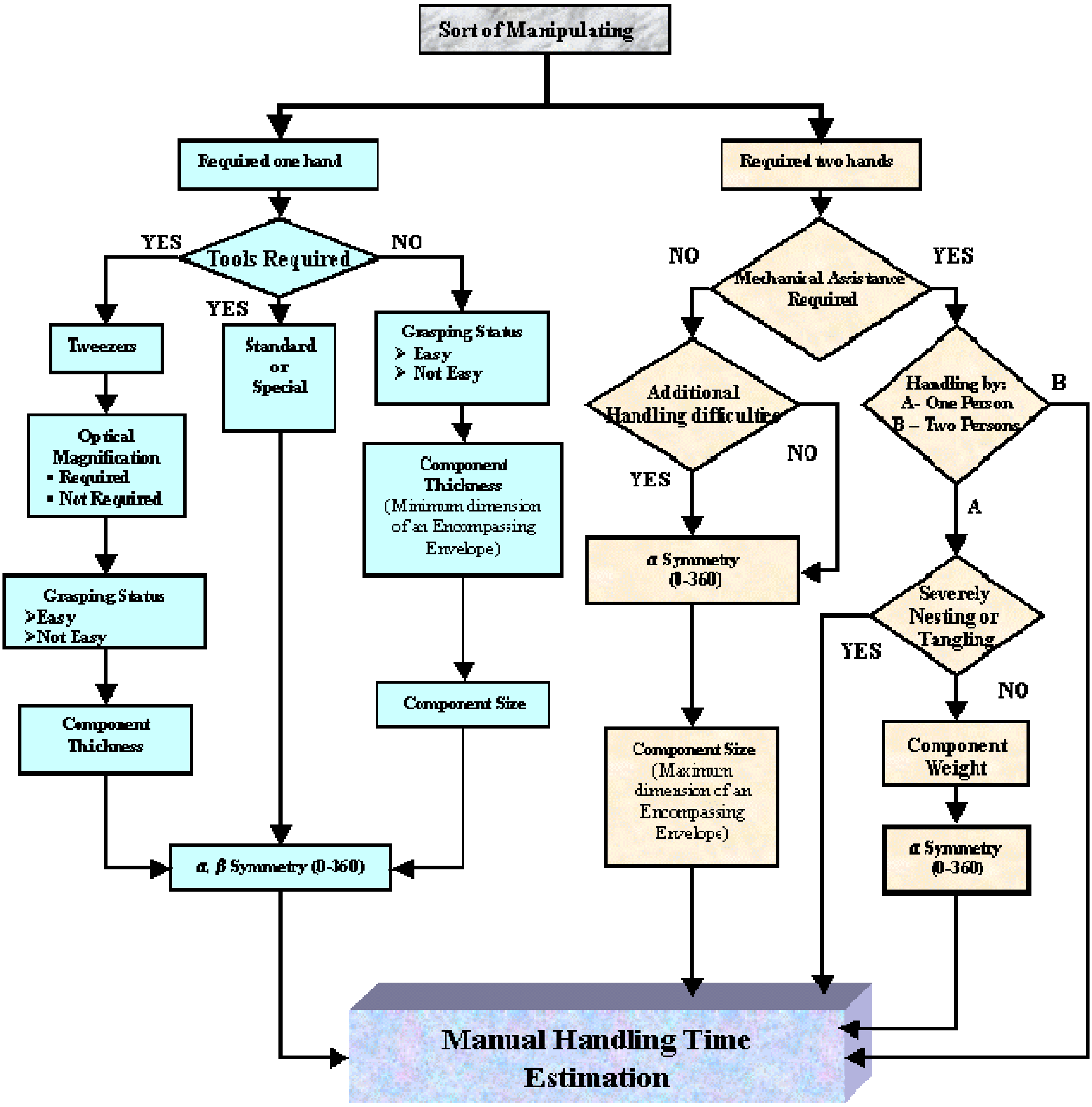


Figure (5.19) Stages of Manual Handling Time Estimation

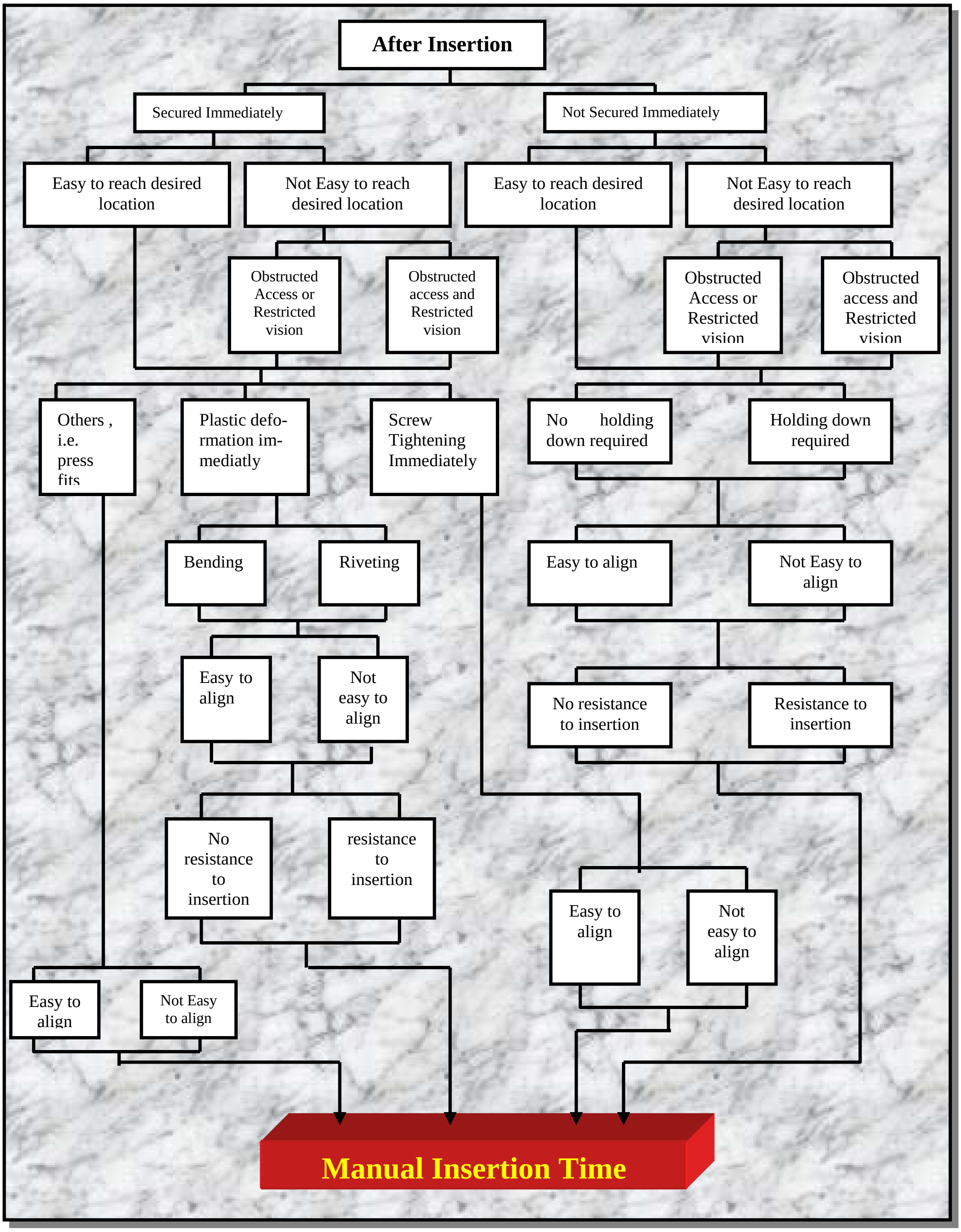


Figure (5.20) Stages of Manual Insertion Time Estimation

Step 5: The system calculates the total operation time, in seconds, by adding the handling and insertion times that were estimated in steps 3 and 4 and multiplying this sum by number of repeated operations

$$\text{Total operation time} = (\text{MHT} + \text{MIT}) * \text{number of repeated operations} \qquad (5.\ 2)$$

Step 6: The system calculates the total operation cost by multiplying the operation time, estimated in step 5, by the operator rate. The operator rate is the annual operator cost including overheads divided by the total seconds per year for one shift. Total seconds per year for one shift equal to 7.2 million seconds. It is estimated based on 8 hours per shift and 240 working days per year.

$$\text{Total operation cost} = \text{Total operation time} * \text{Operator rate} \qquad (5.\ 3)$$

Step 7: The total assembly cost is estimated automatically by the summation of the operation cost for all components.

$$\text{Total manual assembly cost (CM)} = \sum_{P=1}^{P=n} \text{Total operation cost} \qquad (5.\ 4)$$

Where (P=1) for the first component that be analysed and (P= n) for the last component that be analysed.

5.7 Cost Analysis for Automatic Assembly

This section shows how a design is analysed. If the values of the basic product and production parameters have indicated, that automatic assembly using high-speed automatic assembly, is likely to be economic, then this normally means that high production volumes are required. The technique used involves systematic classification of the features of the design in order to estimate the full cost of automation. The technique also identifies areas for possible improvement through re-design. In the analysis for automation, the classification systems, for handling and insertion processes, provide cost indices for component design classes. This gives an indication of the relative cost of the equipment required to automate the process. Figure (5.21) shows the processes of cost estimation for automatic assembly.

5.7.1 Procedure for the Automatic Assembly Analysis

The steps required for a cost estimation are as follows:

Step 1: Obtain the best information about the product or assembly, Engineering drawings, exploded three-dimensional views, an existing version of the product or a prototype.

Step 2: Assign an identification number to each component. If the assembly contains sub-assemblies treat these, at first, as "components" and then analyse the sub-assemblies later.

Step 3: Assign the required assembly rate (FR) by asking the user/designer.

Step 4: Identify the type of component, whether the component is rotational or not. The dimensions of the component also are identified by asking the user, via the system.

Step 5: The system classifies each kind of component separately by the use of interrelated rules that are inserted into system, i.e. whether rotational as (disc, short cylindrical, long cylindrical) or not rotational as (flat, long cubic, cubic).

Step 6: Estimate the feed cost (FC) and orientation efficiency (OE) for each kind of component separately (rotational, non-rotational). This is carried out automatically using the proposed system. When the component feeding and orienting analysing is completed. Then the system enables the estimation of feed cost and orientation efficiency through interrelating rules, that are inserted already into the system.

The criteria for FC and OE estimations are based on the features of the component as shown in Figure (5.22) for rotational components and Figure (5.23) for non-rotational components. Rotational components are analysed for the type of component (disc, short

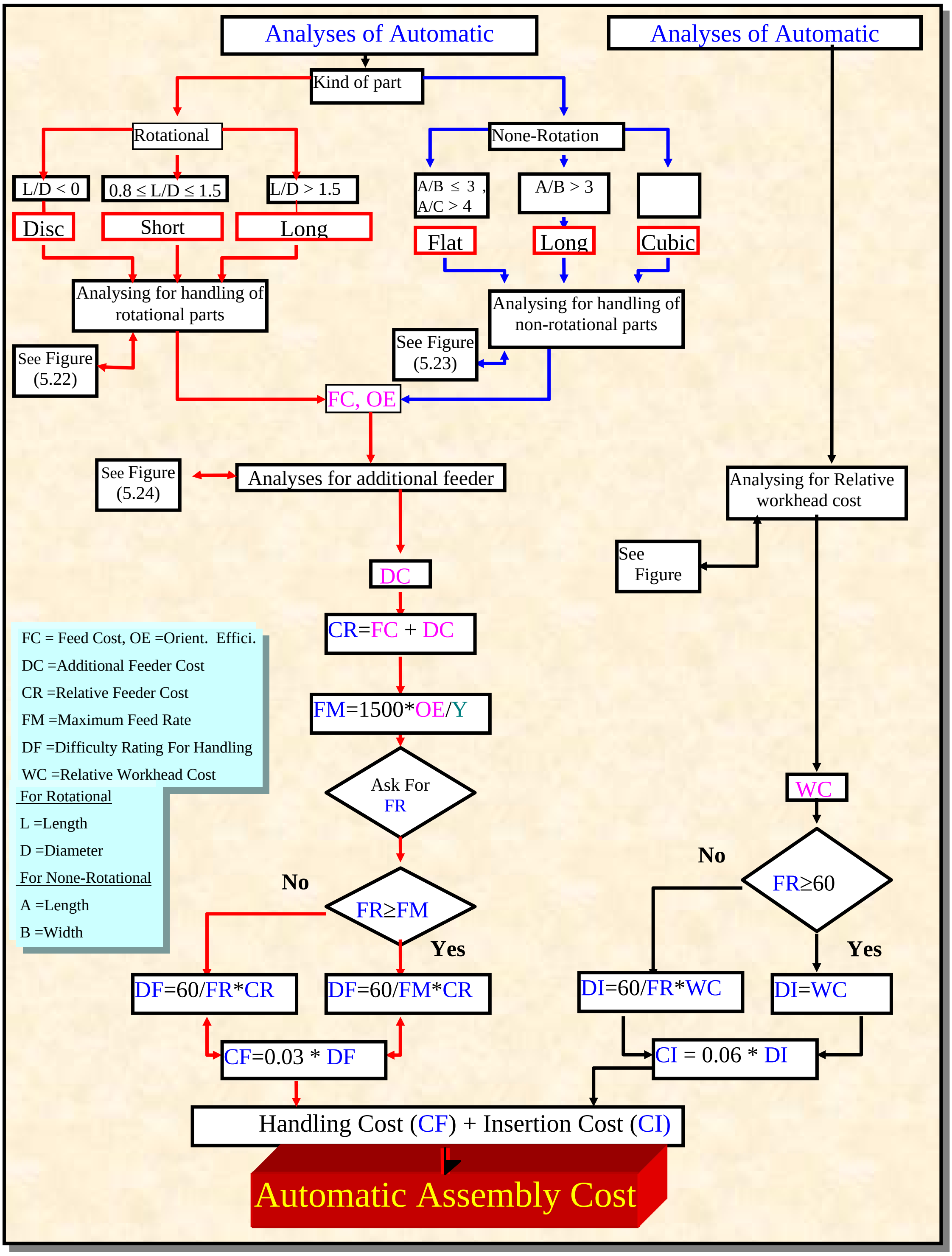


Figure (5.21) Processes of Automatic Assembly Cost Estimation

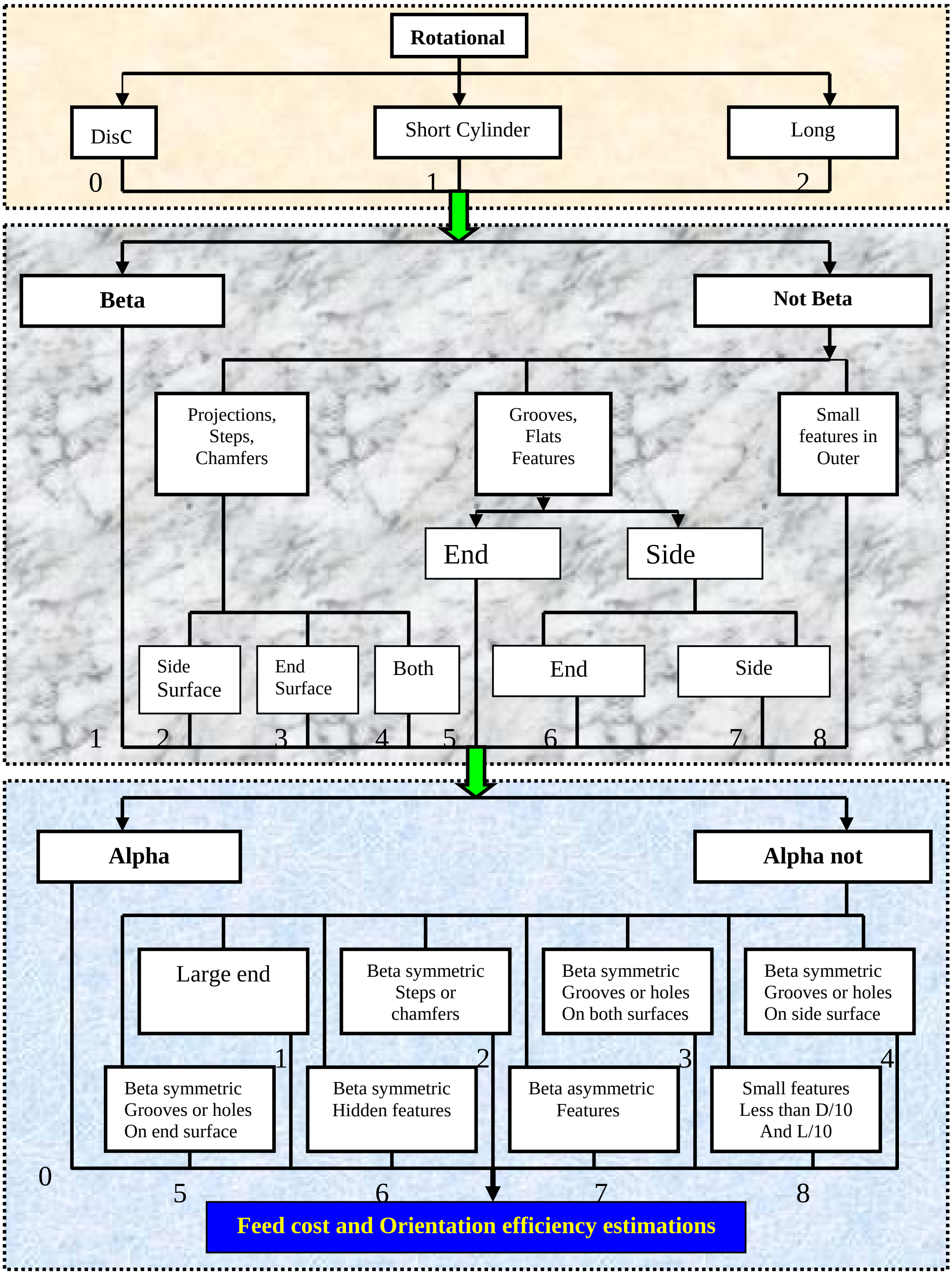


Figure (5.22) Feed Cost and Orientation Efficiency Estimations for Rotational Components

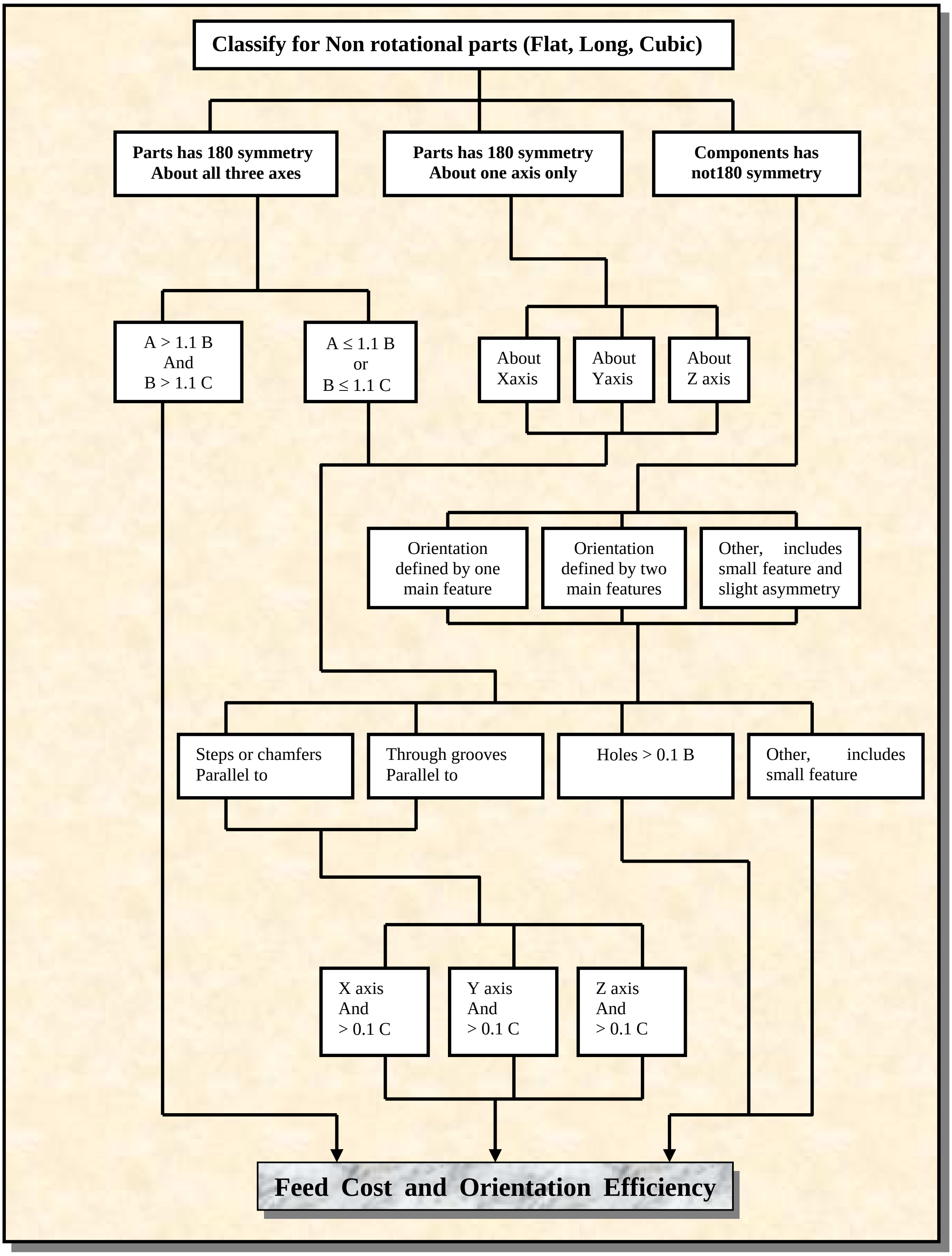


Figure (5.23) Feed Cost and Orientation Efficiency Estimations for non-Rotational Components cylinder or long cylinder), whether or not the component is beta symmetric, component features such as projections, steps, chamfers, grooves, flats, very small features, location of component features (side surface, end surface) and whether or not the component is alpha symmetric.

The following rule illustrates the use of interrelating rules, in the system, to estimate FC and OE for rotational components.

FC_OE_Rotational_Rule_1:

If *(the component is a short cylinder)* *AND*
(the component is not beta symmetric) *AND*
(the feature of component is a projection) *AND*
(the feature is located on side surface) *AND*
(the feature is alpha symmetric)

Then *(the feed cost (FC) is equal = 0.63 pence)* *AND*
(orientation efficiency (OE) is equal = 0.15)

An example of how interrelating rules were used in the system to estimate the FC and the OE for non-rotational components is presented below:

FC_OE_NonRotational_Rule_1:

IF *(The component is cubic)* *AND*
(The component has 180° symmetry about one axis only) *AND*
(The axis that classifies the symmetry is the X axis) *AND*
(The main feature that defined the orientation is chamfer) *AND*
*(The feature is parallel to X axis and > 0.1 * C)*

THEN *(The feed cost is equal = 0.63 pence)* *AND*
(Orientation efficiency (OE) is equal = 0.4)

Step 7: This is the step that estimates the additional feeder cost (DC). This is estimated automatically by the system. When analyzing the difficulties of feeding the component, the system allows estimation of the additional feeder cost through interrelating rules that are inserted into the system.

The criterion for DC estimation is based on the complexity of component (see Figure (5.24)). The analysis for additional feeding involves, whether the component is abrasive or not, whether the component is small or large, whether the component is tangled or nested or severely tangled or severely nested or not together with the characteristics of component (light, sticky, delicate, flexible, tend to overlap). The following rule illustrates one of interrelating rules in the system for estimating the additional feeder cost DC.

DC_Rule_1:

If *(The component is small and non-abrasive)* *AND*
(The component is not tangled or nested) *AND*
(The component is light) *AND*
(The component is not sticky) *AND*
(The component does not tend to overlap) *AND*
(The component is not delicate) *AND*
(The component is not flexible)

Then *(the additional feeder cost is equal to 1.87 pence)*

<u>Step 8:</u> The system calculates the relative feeder cost (CR) from the summation of feed cost (FC), calculated in step 6, and the additional feeder cost (DC), calculated in step 7.

$$\mathbf{CR = FC + DC} \tag{5. 5}$$

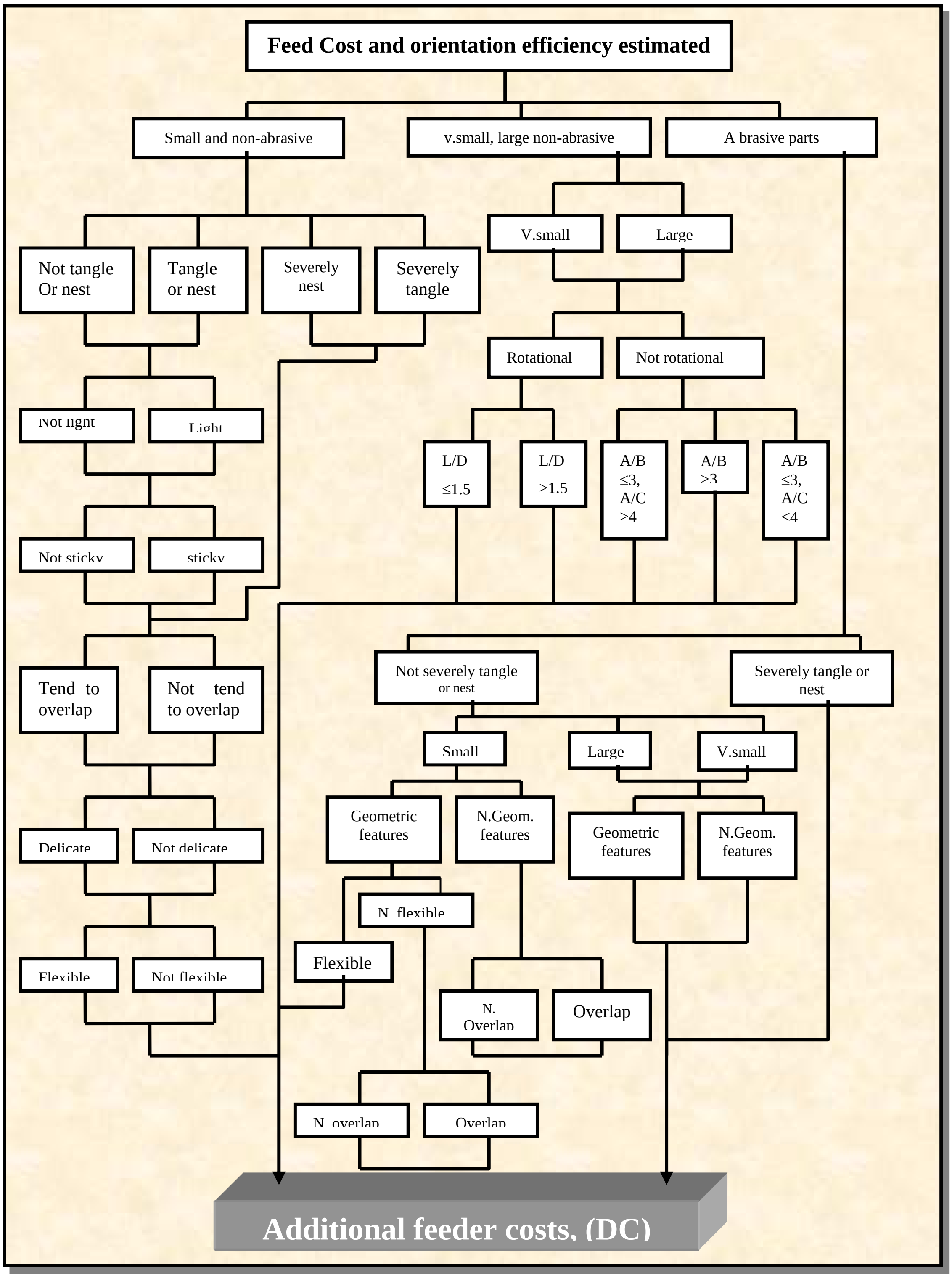


Figure (5.24) Stages of Estimation of additional Feeder Cost (DC)

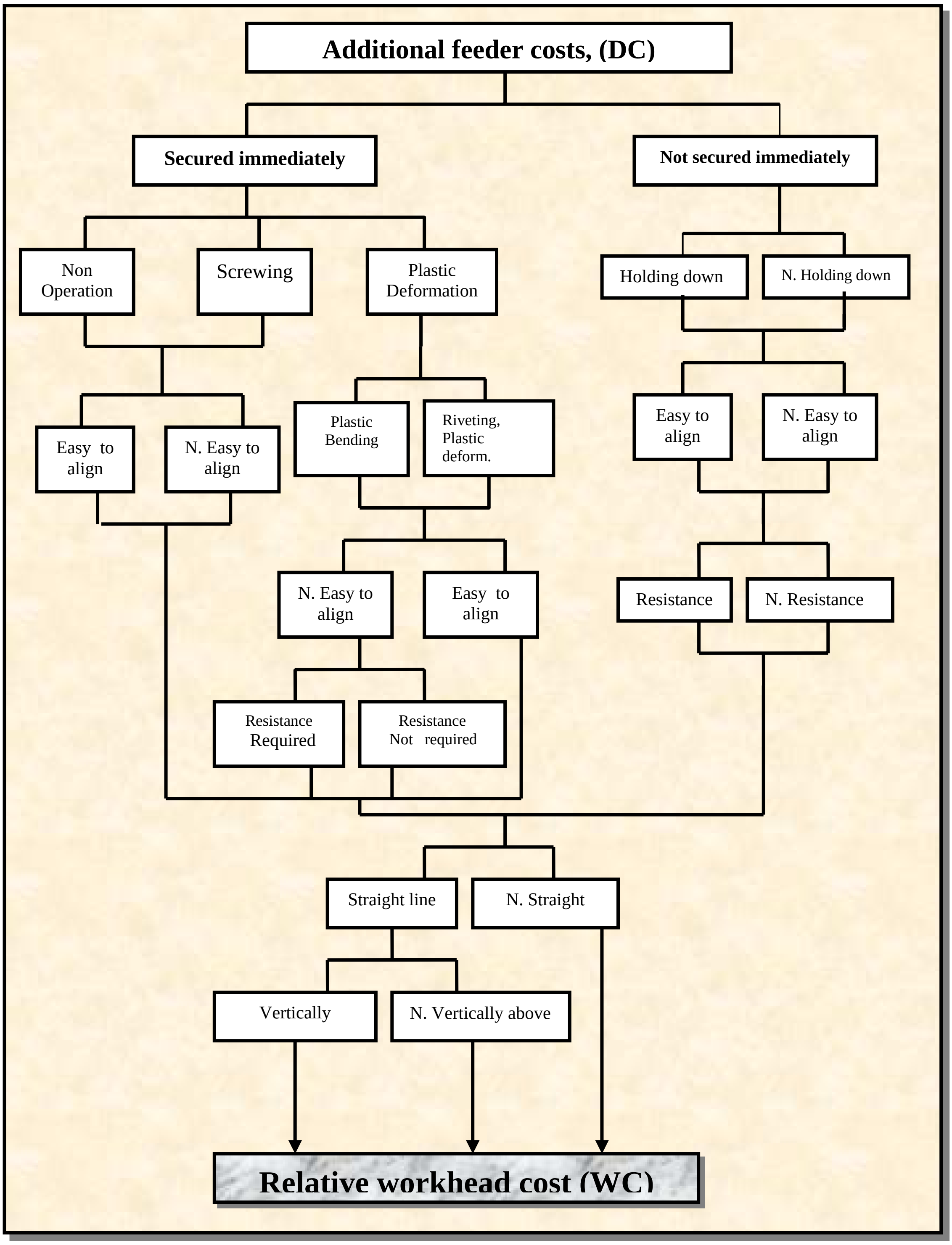


Figure (5.25) Stages for Estimation of Relative Work-head Cost (WC)

Step 9: The system calculates the maximum basic feed rate (FM), for a standard feeder when the components are traveling at 25 mm/s, using the following equation:

$$\mathbf{FM = 1500 * OE / Y} \qquad (5.\ 6)$$

Where Y = the size of component

OE = orientation efficiency (step 6)

Step 10: The system calculates the difficulty rating (DF). It is estimated by using one of two rules. The first rule is used when the required feed rate (FR) is less than or equal to the maximum basic feed rate (FM), and the second is used when FR > FM. If FR is less than FM then a further increase in cost will be incurred.

$$\mathbf{DF = (60/FR) * CR} \qquad \text{If } FR <= FM \qquad (5.\ 7)$$

$$\mathbf{DF = (60/FM) * CR} \qquad \text{If } FR > FM \qquad (5.\ 8)$$

Step 11: The system calculates the cost of automatic handling per component (CF) by multiplying the difficulty rating (DF) by the cost of the standard feeder, for one second (CSF), and is equal (CSF = 0.02 pence typically)

$$\mathbf{CF = DF * CSF} \qquad (5.\ 9)$$

$$\mathbf{CF = DF * 0.02} \qquad (5.\ 10)$$

For cost calculation, in this step, it is assumed that this basic feeder is fully operating on an assembly machine would cost £3125. If this cost were amortised over 28 months on 1 shift working then each 25-mm cube would cost approximately 0.02 pence to feed and orient.

Step 12: This step estimates the relative work-head cost (WC) which is necessary to estimate the cost of automatic insertion and is estimated automatically by the proposed system, by analysing the component for automatic insertion. A set of interrelating rules in the system is used to estimate the relative workhead cost (WC).

The criteria for WC estimation is based on the assembly features during and after insertion (see Figure (5.25)). These include, whether or not:

The component is secured immediately after insertion,

- The component requires holding down,
- The component is easy to align,
- The component has resistance to insertion,
- If any sort of assembly operation required after insertion (e.g. screwing, riveting, bending, others),
- Only one motion is required for insertion,
- The insertion direction is from vertically above.

The following rule is illustrative of interrelating rules in the system to estimate WC:

WC_Rule_1:

If *(The component is not secured immediately after insertion)* *AND*
(The component requires holding down after insertion) *AND*
(The component is not easy to align) *AND*
(The component has resistance to insertion) *AND*
(The insertion direction of the component is straight line) *AND*
(The component inserted from vertically above)

Then *(The relative work-head cost is equal to 1.44 pence)*

Step 13: The system calculates the difficulty rating for automatic insertion (DI) and is estimated using one of two rules. The first rule is used when the required feed rate (FR) is less than 60, while the second rule is used when FR > 60 or equal.

$$\mathbf{DI = (60/FR) * WC} \qquad \text{If FR} < 60 \qquad (5.\ 11)$$

$$\mathbf{DI = WC} \qquad \text{If FR} \geq 60 \qquad (5.\ 12)$$

Step 14: The system calculates the cost of automatic insertion per component (CI). It is estimated by multiplying difficulty rating for automatic insertion (DI) by the cost of standard insertion work-head for one second (CSI), and is equal (0.06)

$$\mathbf{CI = DI * CSI} \qquad (5.\ 13)$$

$$\mathbf{CI = DI * 0.06} \qquad (5.\ 14)$$

In this case the work-head, installed and operating on assembly machine is assumed to cost approximately £ 6,250. If this cost is amortized over 28 months on 1 shift working, then each operation of 1 second duration will cost 0.04 pence.

Step 15: The system calculates the operation cost in pence by the summation the cost of automatic handling (CF) and the cost of automatic insertion (CI) and multiplying this sum by number of repeated operation

Automatic operation cost = (CF) + (CI) * number of repeated operation (5. 15)

Step 16: The total automatic assembly cost is estimated automatically by the summation of the operation cost for all components.

$$\textbf{Total assembly cost (CA)} = \sum_{P=1}^{P=n} \textbf{automatic operation cost of each component} \qquad (5.\ 16)$$

Where (P=1) for the first component that be analysed and (P= n) for the last component to be analysed.

5.8 Robotic Assembly

One of the possibilities for reducing the total production cost, for a product, is to automate the assembly process. Automated assembly equipment used in mass production, is often referred to as *dedicated* equipment. Automated assembly of the more flexible kind is referred to as *programmable* or *adaptable assembly* or just *robot assembly*. Currently all robot assembly applications use robots as dedicated equipment, and the basic programming of the robot might be carried out only during initial set up of the system. Occasional reprogramming to allow for design changes or style variations is also used. The term *special-purpose* is used to describe equipment or tooling that is custom-made for one product or component and the term *general-purpose* is used to describe equipment or tooling that can be readily adapted or programmed for a variety of products or components (Boothroyd (992)). The robot's basic operations can be considered as a cycle of six operations, feeding, picking up, moving, composing, releasing and moving.

5.8.1 Advantages and Process Capability of Robotic Assembly

Some of the main advantages, in the use of the assembly robots, can be categorised as follows (Boothroyd (1992)):

- ❑ **Stability of the product design.** If the product design changes, a robot can be reprogrammed accordingly. However, this does not usually apply to the peripheral items in the system that contact the components, such as feeders, grippers, etc.

- ❑ **Production volume.** A robot system can operate economically at much longer station cycle times than a high-speed automatic assembly machine. The station cycle time is the interval between the production of completed assemblies.

- ❑ **Style variations**. A robot system can more readily be arranged to accommodate various styles of the same product. For example, the robot can be reprogrammed to select only certain components for the assembly, depending on the particular style required.

- **Component defects.** It has been noticed that a feeder jam caused by a faulty component causes much greater loss in production on a high-speed transfer assembly machine than on a robot system with a relatively long cycle time. In addition, the robot can be programmed to sense problems that may occur and to reattempt the insertion procedure.

- **Component size.** A principal advantage of a robot used in assembly is that the components can be presented in patterns or arrays on pallets or component trays. In this case, the severe restrictions on component size in high-speed automation do not apply.

Robots are not generally capable of exerting large forces or torque such as those needed for heavy press fits or self-tapping operations into thick gauge or hard materials. However, it should be noted that there are some insertion processes, a robot cannot perform without the aid of special work-stations. These would include, for example, all insertion or fastening operations requiring the application of large forces. Also, there are some processes that a robot cannot perform adequately without using special tools. These include screw insertion and spot-welding. For many of these, a single-component special-purpose work-head can be used that is a mechanism or machine designed to perform the insertion operation repeatedly.

5.8.2 Component Presentation for Robotic Assembly

In the automatic assembly of one component, there are two principal steps:

- The handling and presentation of the component to the insertion device
- The insertion of the component.

Depending on circumstances, either or both of these steps might be carried out automatically, and the last step (insertion) might be carried out by an assembly robot. It is useful to consider the alternatives for the automation of the insertion operation, assuming first that the components can be presented at the required frequency and in the same orientation. On the other hand, there are some operations that require complicated manipulations so that a robot under program control is essential. These include following a contoured seam in welding or running a wire through a complicated path.

The more fundamental difference between a robot and a single-component special-purpose work-head, is that the work-head can perform only the one operation repeatedly, whereas the robot can perform a sequence of different operations repeatedly.

In robotic assembly, the method used for presenting each component must be decided. There are three techniques for component presentation, namely:

- PF : Programmable feeder
- SF : Special- purpose feeder
- MG: Manually-loaded magazine, pallet, or component tray.

For multi-station robotic assembly system, new component presentation methods must be assigned at each new station, regardless of whether the same component has been presented earlier. The use of automatic feeders is likely to be more economic on multi-station machines because of the shorter cycle times.

5.8.3 Cost Analysis of Robotic Assembly

Robots can reduce assembly costs. But as any other assembly process, robot-based technique must be taken into consideration at the design stage. In order to determine robotic assembly costs, it is necessary to obtain the total cost of all general and special purpose equipment and the average assembly cycle time as well as the manual labour cost per assembly. Figure (5.26) shows the effect on the assembly processes such as difficulty of component placement, direction of assembly and the difficulty for insertion, on assembly cost and time of robotic assembly system. There are normally three basic robot assembly systems namely, single station with one arm robot assembly system, single station with two arms robot assembly system, and multi-station robot assembly system. The following section demonstrates how the robot assembly cost can be estimated.

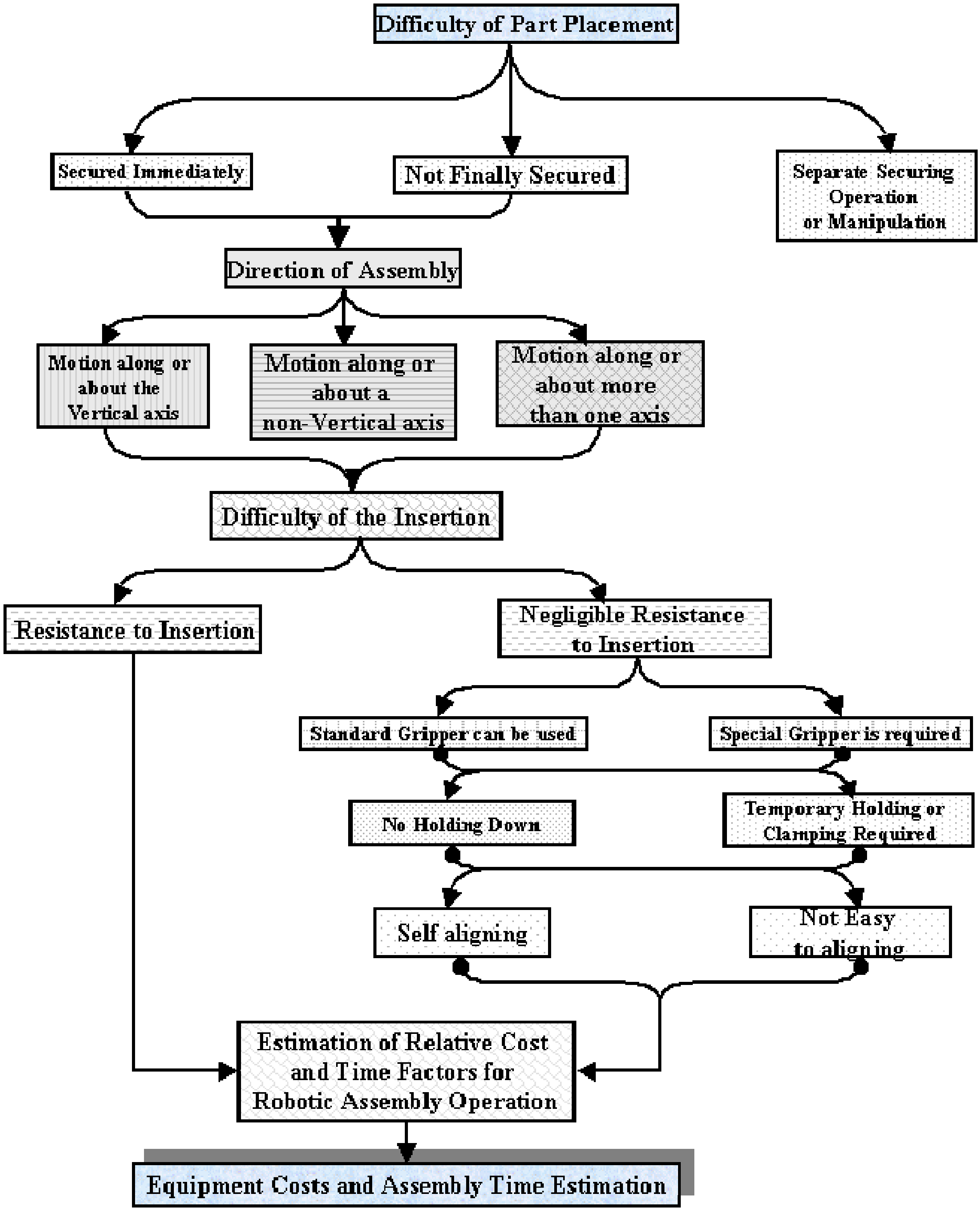


Figure (5.26) The Effect of Component Factors on Assembly Cost and Time of a Robotic Assembly System

5.8.3.1 Procedure for a Robot Assembly System

The procedure of cost estimation for robot assembly system are presented as following:

Step1: Obtain the best information about the product from, Engineering drawings, Exploded 3-D views, an existing version of the product, or a prototype

Step2: Assign an identification number to each component in reverse order of assembly

Step3: This step is used to estimate the parameters required to perform the insertion operation. These parameters are, the relative robot cost (AR), the relative additional gripper or tool cost (AG), and the relative effective basic operation time (TP).

Step4: The system estimates the total operation time (TA) for a component as follows:

$$TA = TB * (TP + TR) \qquad (5.\ 17)$$

Where:

TB = basic robot operation time,

TP = relative effective basic operation time

TR = relative time penalty for final orientation by the robot (typical values are 0, 2 or 3 sec).

Step5: The system accumulates the values of TA for one station and assigns it to TAS.

Step6: The system ascertains the maximum value of (TAS) and considers it as the assembly cycle time (TAT) (neglecting downtime).

Step7: Based on the number of shifts-year that the user input, the system calculates the general-purpose equipment rate (RC).

$$RC = 0.014/PS \text{ pence/sec} \qquad (5.\ 18)$$

Where: PS = Number of working shifts-years for amortisation of equipment.

Step8: The cost per component assembly of using the general-purpose equipment (CST(GP)) is obtained from the following:

$$CST(GP) = ((ROB1*ARM + CT) * TA/TAS + CGP) * (RC*TAT) \quad (5.\ 19)$$

Where:

ROB1 = Cost of a standard robot,

ARM = Maximum value of AR for one robot station,

CT = Cost of one station on free-transfer machine including buffers and controls,

CGP = Cost of general-purpose portion of components presentation equipment. For a vibratory bowl feeder, it is the cost of the drive unit. For a programmable feeder, it is the cost of the drive unit and general-purpose tooling,

Step 9: The cost per component assembly of using special-purpose equipment (CST(SP) is given by:

$$(CST(SP)) = 100* (CWC * TA/TAS + CSP + CG*AG)/BS \quad (5.\ 20)$$

Where:

CWC = Cost of special work carriers associated with one station on a multi-station system,

CSP = Cost of special-purpose portion of components presentation equipment. For a vibratory bowl feeder, it is the cost of the drive unit. For a programmable feeder, it is the cost of the drive unit and general-purpose tooling,

CG = Cost of a standard gripper,

AG = Relative cost of additional gripper or tool,

BS = Batch size in thousands.

Step 10: The manual worker or operator costs per component assembly (CST(OP)) is given by:

$$(CST(OP)) = TT*OP \quad \text{pence} \quad (5.\ 21)$$

Where:

TT = Manual handling and insertion time or manual operator time for component handling and easy insertion into magazine or pallet,

OP = Manual operator rate. It is the annual operator cost including overheads divided by the total seconds per year for one shift. Total seconds per year for one shift equal to 7.2 million seconds. It is estimated based on 8 hours per shift and 240 working days per year.

Step 11: The system calculates the total assembly costs per component or subassembly.

Step 16: The total automatic assembly cost is estimated automatically by summation of the operation cost for all components.

$$\textbf{Total assembly cost (CR)} = \sum_{P=1}^{P=n} \textbf{robot operation cost of each component} \qquad (5.\ 22)$$

Where (P=1) for the first component that be analysed and (P= n) for the last component that be analysed.

5.9 The Scenario for Design Analysis for Automation

The scenario for analysing a product for design for assembly is commenced by specifying the basic product specifications and the production data (production volume, number of components. etc.). Based on these data the system selects the most economic assembly technique for that specific product. As stated earlier detailed knowledge of the product design is not required to select the assembly method selection. The reason that early assembly selection is important is that manual assembly differs widely from automatic or robotic assembly in the requirements it imposes on the product design. The recommended assembly method is examined in the early stages of the design process to ensure it is considered in the product design process. The system scenario is illustrated in Figure (5.27).

The system was designed in such a way to allow designers to analyse the product economically for the selected assembly method i.e. manual, robotics or high-speed automatic. Production rules, developed specifically for each of these techniques, used to obtain the data that in turn are used to assess the components in the design, for ease of handling and insertion. For instance, in the case of analysis the product for manual handling and insertion, assessment is based on estimating manual assembly costs, using time data corresponding to particular component design specifications together with operator wage rates.

The system has the capability of carrying out design feasibility and providing design improvement suggestions for robotic assembly to manufacturing companies. The designer/user interacts with the system through a well designed user interface which allows to input of the product and process properties. The product and process properties are differentiated into component, assembly, and process properties. The design criteria for robotic assembly have been applied for each component. In other words, the separate subassemblies and components, as well as the whole assembly are technically evaluated based on the score of each component. The system can identify, automatically, the components with relatively highest total scores, so as to initiate the suggestions for redesign. Then a design analysis report is generated for the designer. Attention in the redesign stage in robotic assembly focuses upon the relatively highest component scores. The various components in assembly operations are considered for redesign, to simplify the assembly process, including the feeding, handling, and composing processes. The property with highest score, for a component, indicates that this property must be subjected to redesign. A series of design modifications are proposed with the purpose to simplify the assembly process.

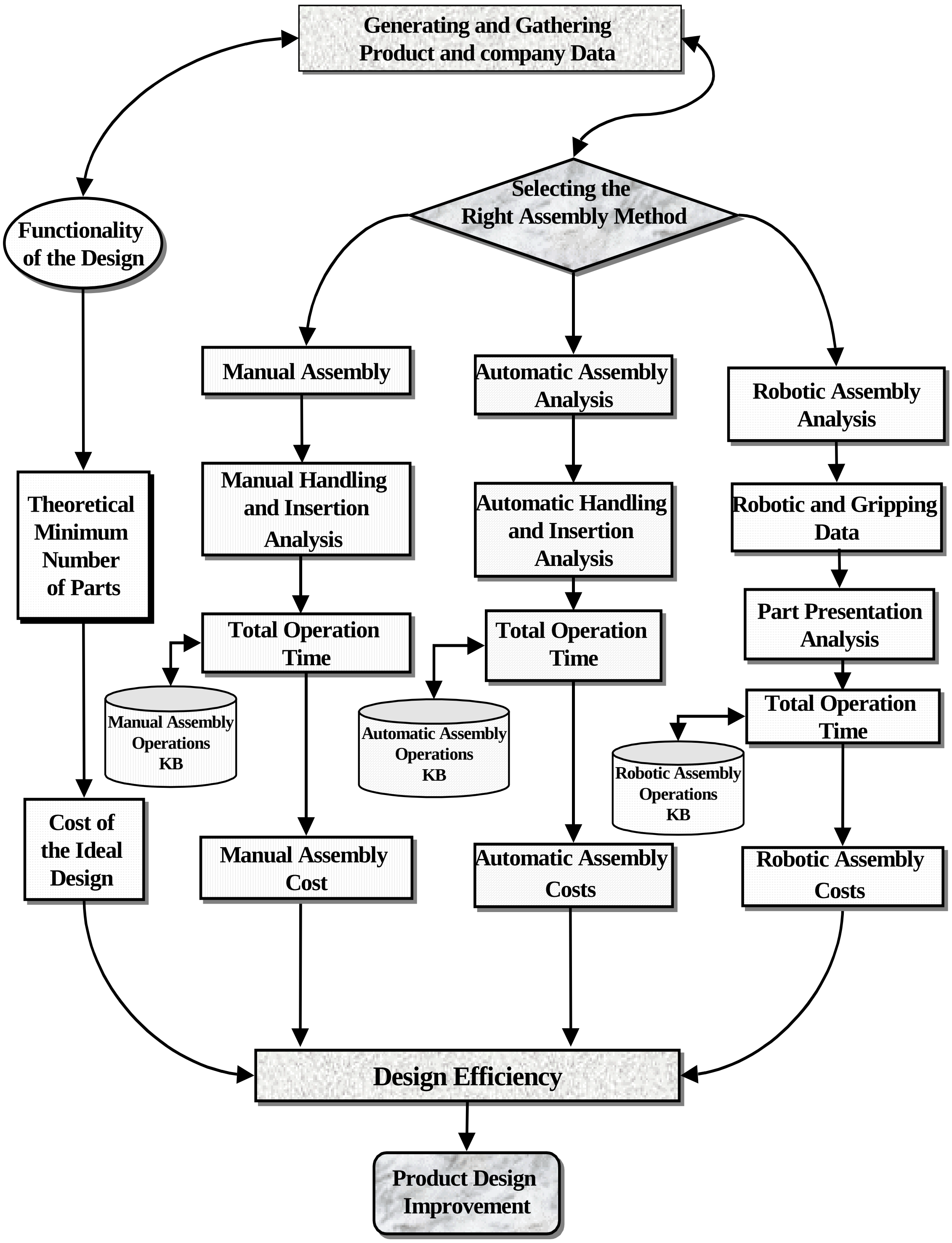


Figure (5.27) The System Scenario for Design for Assembly

5.10 Conclusion

This chapter introduced the application of a knowledge-based system for design for automation within a concurrent engineering environment, in order to give designers the possibility to assess and reduce the total production cost of a product. The developed model for design for automation has been presented. The system framework comprised of CAD system, knowledge-based system, user interface, design analysis for automation module, and design improvement suggestion module. Hybrid knowledge representation techniques, including production rules, frames and object oriented were employed to represent various types of assembly knowledge in this research. The scenario for the system and the main stages of system execution were discussed. The various stages that calculate the main factors of assembly cost were also set out. The novel model, which is described in detail in this chapter, meets the objectives set out in Section 1.5 by containing the following capabilities:

- It provides the designer with the facility to select the most economic assembly technique, for the product, based on the basic product specifications and the production data (production volume, number of components. etc.), at the early stages of the design process.

- Estimating the assembly time and cost for manual, high-speed automatic, and robotic assembly techniques.

- Analysing the product design for automation. Assembly automation and robotic assembly are highly specialised fields, and most designers do not have the necessary knowledge to meet all requirements to achieve a good design from the assembly point of view. This system provides this need.

- It provides the designers with design improvement suggestions to simplify the assembly operations.

- It provides designers with complete and rapid results for selecting the assembly technique together with the assembly time and cost estimation, design analysis for automation and redesign suggestion via a user-friendly interface.

In conclusion, this model included the above capabilities, which had not been applied by previous research and provided a novel approach for design evaluation and redesign suggestions of a product for assembly automation at early design stage.

CHAPTER 6

6 VALIDATION OF THE DEVELOPED SYSTEM

6.1 Overview

The aim of this chapter is to both validate and demonstrate the capability of the developed system through five case studies. This capability includes product cost estimation including the assembly cost, selection of the most economic assembly technique, design analysis for automation, and the provision of design improvement suggestions, for easy assembly. This chapter pulls together the techniques and procedures, which were discussed in the previous chapters. It demonstrates how users can implement the system easily and efficiently.

6.2 Introduction

The developed system enables the designers, besides estimating the manufacturing cost of a product, to analyse the product design for ease of assembly. Five different examples were chosen for the case studies. The reason is that to illustrate the system capabilities for analysing a product design for assembly, and estimating the manufacturing cost of injection moulded components as well as machined components.

The first case study focuses upon designing a product for assembly. A scientific calculator was the domain chosen as a case study for validating the developed product cost modelling system. The system begins with analysing the product for ease of assembly. The system then recommends the most economic assembly technique. Based on this recommendation, the system estimates the assembly time and cost required for assembling the calculator.

Two case studies concentrate upon the manufacturing cost modelling of injection moulded components. Here the front cover of the calculator and a telephone handset are used as examples in order to estimate the cost of moulding.

In order to demonstrate the capability of the developed cost-effective design environment for machined components, two examples were used. These examples are a Transmission-Transfer Block and a Socket. To determine the accuracy of the cost estimation by the system, the transmission-transfer block was machined using a CNC milling machine at the workshops of De Montfort University. An example of the starting up window of the system is shown in Figure (6.1).

Figure (6.1) The Software Starts Up Window

6.3 Case Study 1: Design Analysis of a Scientific Calculator for Assembly

The design analysis of this product is carried out to ensure that the product is designed for the most economic assembly technique. In addition, suggestions for design changes and assembly recommendations are provided to facilitate ease of assembly. This section shows how the design for assembly module can be used to provide feedback to designers about assembly technique selection and design improvements for automation.

6.3.1 The Product Structure

An exploded diagram of the product was first created on a CAD system (in this study, AutoCAD) as shown in Figure (6.2). It shows that the product consists of fourteen components, and that two joining methods were used. These were snapping and screw connections.

The assembly structure for complete assembly of the Scientific Calculator is shown in Figure (6.3). The assembly structure involves the sequence of and the relationships between single assembly operations. It is determined by the manner in which the product assortment and the product structure are built up from subassemblies and other components, which in turn determine the interrelationships between system components. The analysis and the development of the assembly structure follows from the overview of all single assembly operations which are required to assemble the product (calculator) and as they follow one another in time. The establishment of the correct assembly sequence and the formation of subassemblies are important stages of design for assembly analysis. The development of the assembly structure, for the calculator, presumes that there is specific preference for the sequence of the assembling components. The assembly processes are as follows:

- Mount the 'Front Cover' (component 1) on a fixture, add to it the 'adapter End' (2), the 'Spring' (3), and the 'Keyboard' (4),
- Snapping the 'Spring Foil' (5),
- Add the 'Dome Foil' (6), and the 'Plastic Cover' (7),
- Snapping 'PCB' (8) and tighten the four 'Screws' (9,10,11,12),
- Snapping the 'Rear Cover' (13) and add the 'Battery Cover' (14).

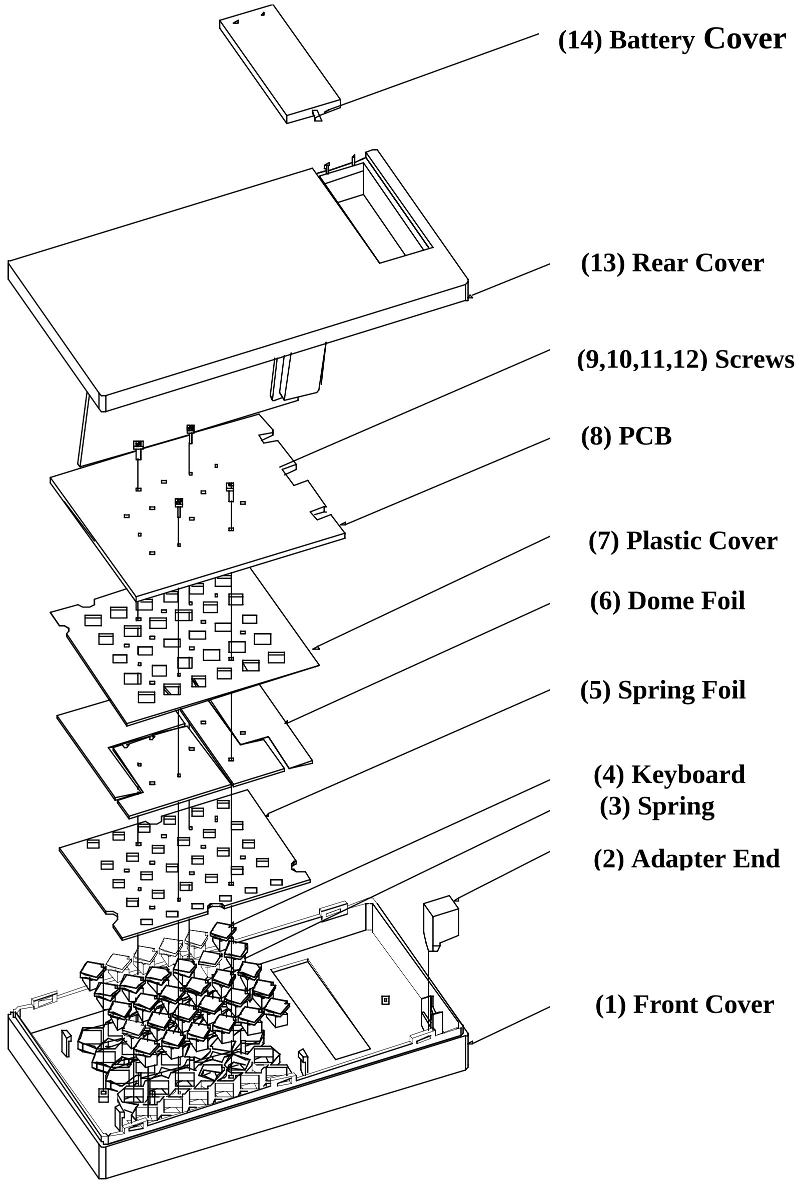
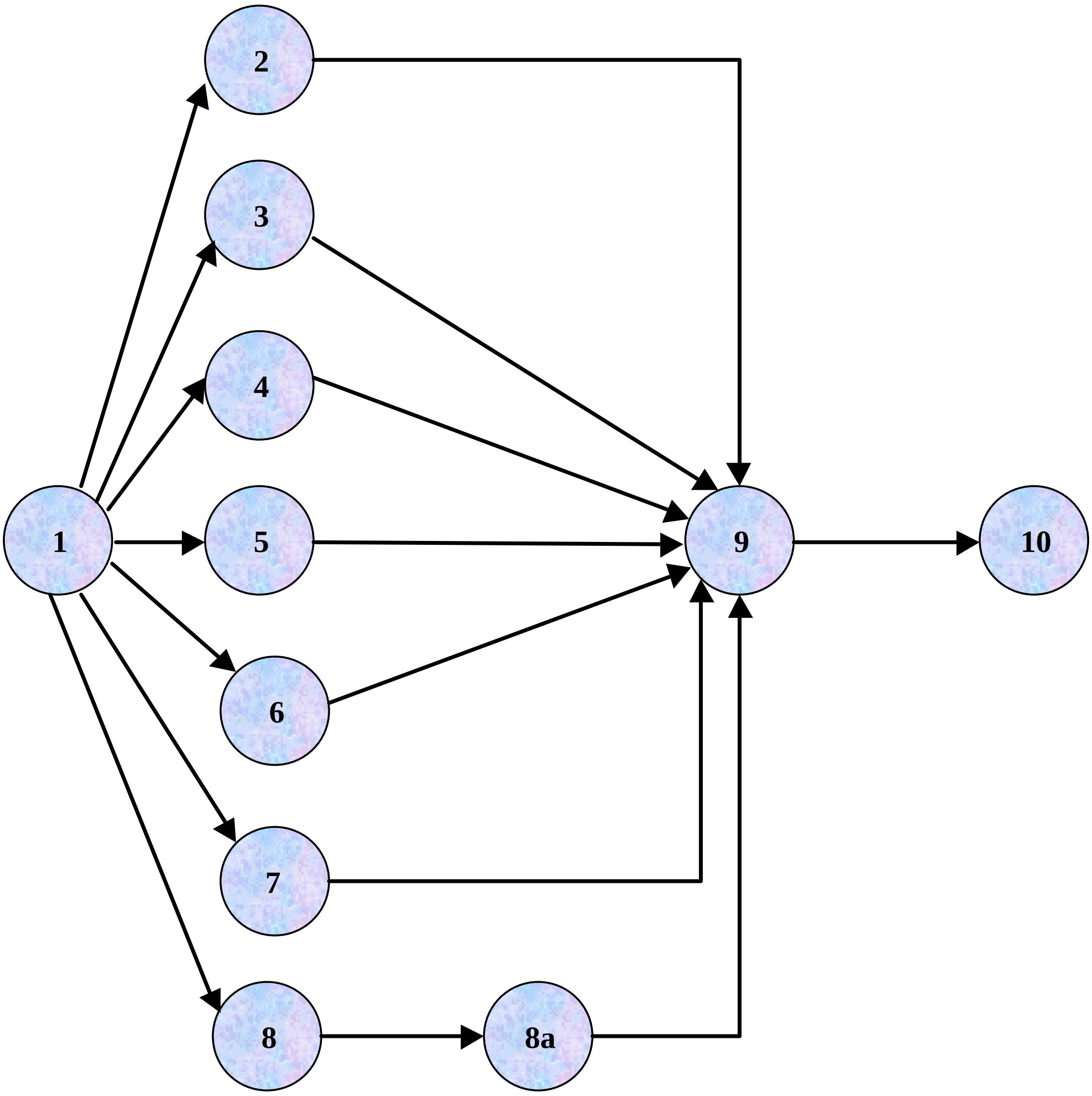


Figure (6.2) Exploded Solid Modelling Diagram of a Scientific Calculator



(1) Load front cover Assembly on the work fixture
(2) Adapter End
(3) Spring
(4) Keyboard
(5) Spring Foil
(6) Dome Foil
(8) PCB
(8a) Screws x 4
(9) Rear Cover
(10)Battery Cover

Figure (6.3) Precedence Diagram for Complete Assembly of the Scientific Calculator

The main aims of analysing the present case study are:

1. To select the most economic assembly technique,
2. To analyse the product for the selected assembly method,
3. To highlight the components that are candidates for redesign,
4. To provide redesign suggestions to simplify the assembly operations,
5. To estimate the assembly time and cost for the final product design.

These are discussed in details in the following sections.

6.3.2 Selection of the Most Economic Assembly Technique

The designer should be aware of the nature of assembly processes and should always have sound reasons for requiring separate components, and these will lead to higher assembly costs, rather than combining several components into one manufactured item.

The reason, that early selection of assembly process is important, is that manual assembly differs widely from automatic or robotic assembly in the requirements that it imposes on the product design. As mentioned earlier an operation that is easy for an assembly worker may difficult for a robot or special-purpose work head (Boothroyd et al. (1987)). The developed system has the capability to recommend the most economic assembly technique in the early stages of the design process. The system selected the most appropriate assembly technique based on the following data that were entered into the system:

Product name . . . . SCIENTIFIC CALCULATOR
Annual production volume 250,000
Number of production shifts. 3
Design style. 5
Number of components. 14
Number of different components. 2
Product market life. . . . . 4 years
Parts defective. . . . . 0.8 %
Annual cost per operator £14,625
Capital expenditure allowances. £25,000

As a result of the design product analysis and the production parameters (production volume, number of components, etc.), the system recommended the robotic assembly system, as the most economic assembly technique for assembling the calculator. Figure (6.4) shows the system output for the recommended assembly technique.

6.3.3 Design Analysis for Robotic Assembly

Assemblability evaluation technique, which discussed in Chapter 5, can be carried out with conceptual drawings. The main objectives of the design analysis of the product were: (1) to ensure that the product is designed for robotic assembly technique, and (2) to facilitate design improvement suggestions for ease of assembly by identifying weak points in the design. The suitability of using robotic assembly for the scientific calculator design is presented in the present section.

The analysis of the calculator design was carried out using the developed system. The assemblability evaluation score methodology was used to assess design quality or difficulty of assembly operation. It is an effective tool to improve the design quality for ease of assembly operations. In the early design stage, weaknesses in the design's assembly producibility are pointed out by this technique.

In this technique, the design criteria for robotic assembly have been applied for each component. In other words, the separate subassemblies and components, as well as the whole assembly are evaluated based on the score for each component. To start the analysis, the component's properties need to be identified and entered into the system. Table (6.1) shows the analysis of the scientific calculator components for the robotic assembly. Figure (6.5) shows the assemblability evaluation report, generated by the system, for the robotic assembly technique. Figure (6.6) illustrates that three components, namely Printed Circuit Board (PCB), Keyboard, and Spring have a relatively high total score of 2177, 1787 and 1768 points, respectively. Redesign of these components is thus necessary to facilitate the robotic assembly operations. The redesign process is discussed in the following section.

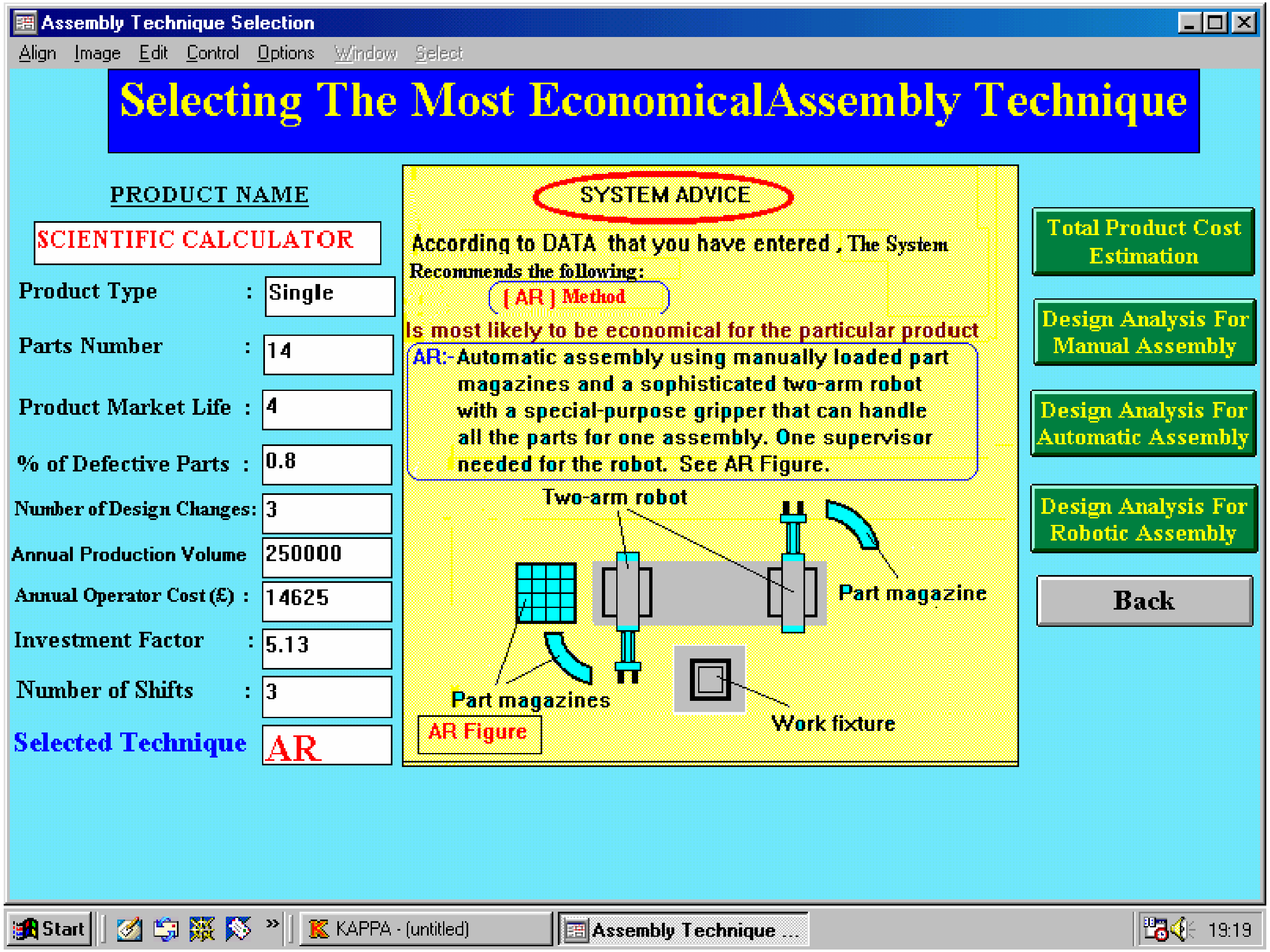
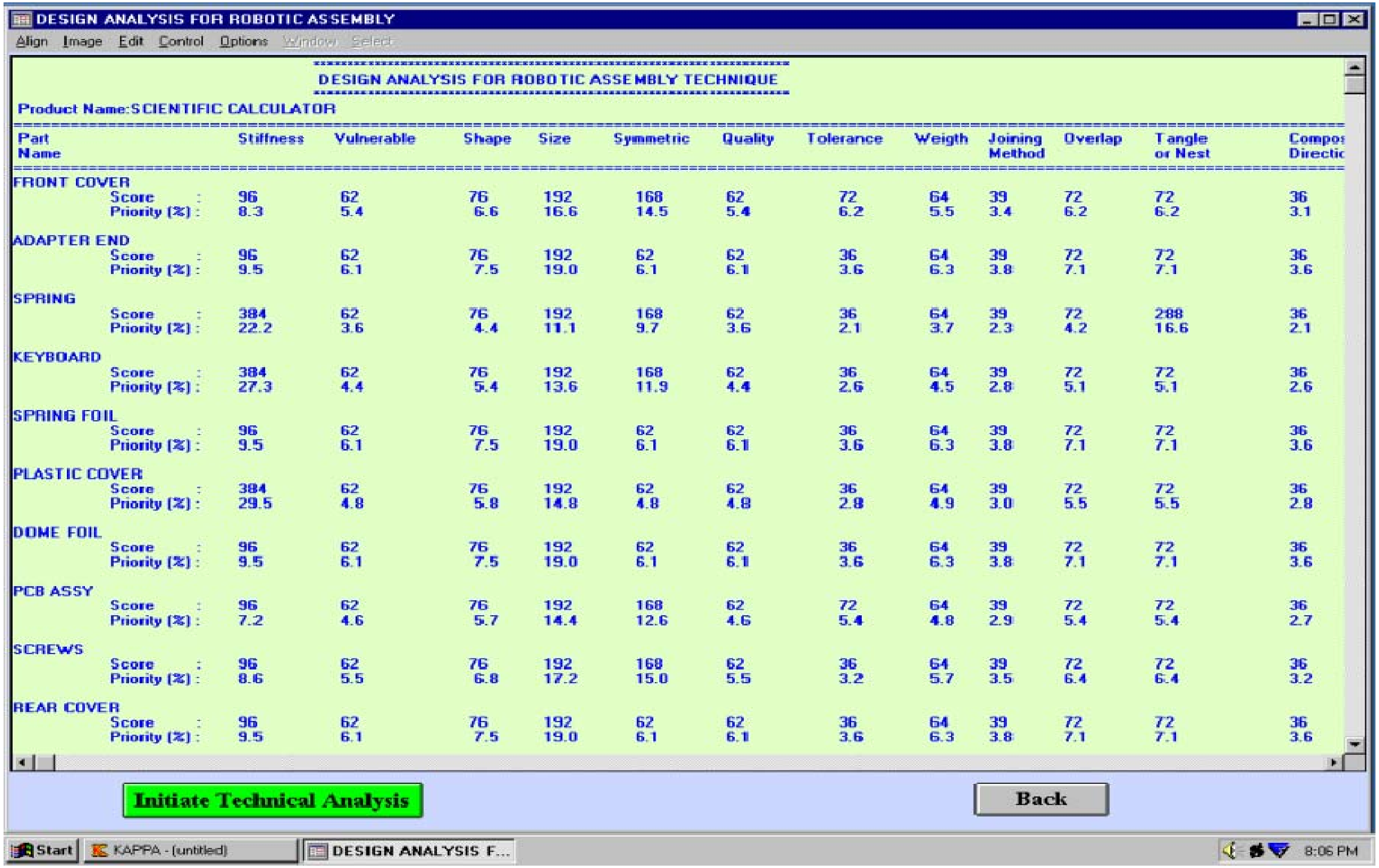


Figure (6.4) The System Window of the Appropriate Assembly Selection for Scientific Calculator

Component ID No.	α-Symmetry	β-Symmetry	Length (A), mm	Width (B),mm	Thickness (C) , mm	A/B	A/C	Weight, gram	Vulner-able: (A) Non-vulnerable (B) Max. drop 200 mm (C) Max. drop 50 mm	Stiffness: (A) non-flexible (B) flexible	Joining Method: (A) snap (B) screwing (C) peg-hole (D) welding, soldering and reveting	Holding down: (A) No holding down (B) Holding down required	Composing movement: (A) Straight line (B) No straight line	Aligning difficulty: (A) easy to align (B) Not easy to align	During feeding: (A) Overlap (B) tangle or nest	Insertion difficulty: (A) No resistance to insertion (B)Resistance to insertion	**Scientific Calculator**
11	360	360	152.2	84	13	1.8	11.7	12.7	A	A	A	A	A	A	NO	A	**Front Assy.**
10	360	360	16.2	10.5	9	1.54	1.8	0.43	A	A	A	A	A	A	NO	B	**Adapter End**
9	180	0	7	3	3	2.3	2.3	0.33	A	B	C	B	A	A	B	A	**Spring**
8	360	360	77	64	3.5	1.2	30.8	0.23	B	B	A	A	A	A	NO	A	**Keyboard**
7	360	360	77	64	2.5	1.2	30.8	4.30	A	B	A	A	A	A	NO	A	**Spring Foil**
6	360	360	79	69	0.35	1.1	225	1.27	A	B	A	A	A	A	NO	A	**Plastic Cover**
5	360	360	73	63	0.5	1.2	146	0.54	A	B	A	A	A	A	NO	A	**Dome Foil**
4	360	360	86	75	2	1.2	43	13.26	A	A	A	A	A	B	NO	B	**PCB Assy**
3	360	0	6	3.8	3.8	1.5	1.5	0.32	A	A	B	B	A	A	NO	A	**Screws**
2	360	360	152.2	84	16	1.8	9.5	8.30	A	A	A	A	A	B	NO	B	**Rear Cover**
1	360	360	62	33	2	1.9	31	1.27	A	A	A	A	A	A	NO	B	**Battery Cover**

Table (6.1) The Analysis of the Scientific Calculator Components for the Robotic Assembly



DESIGN ANALYSIS FOR ROBOTIC ASSEMBLY

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DESIGN ANALYSIS FOR ROBOTIC ASSEMBLY TECHNIQUE

Product Name:SCIENTIFIC CALCULATOR

Part Name		Stiffness	Vulnerable	Shape	Size	Symmetric	Quality	Tolerance	Weigth	Joining Method	Overlap	Tangle or Nest	Compos Directic
FRONT COVER	Score :	96	62	76	192	168	62	72	64	39	72	72	36
	Priority (%) :	8.3	5.4	6.6	16.6	14.5	5.4	6.2	5.5	3.4	6.2	6.2	3.1
ADAPTER END	Score :	96	62	76	192	62	62	36	64	39	72	72	36
	Priority (%) :	9.5	6.1	7.5	19.0	6.1	6.1	3.6	6.3	3.8	7.1	7.1	3.6
SPRING	Score :	384	62	76	192	168	62	36	64	39	72	288	36
	Priority (%) :	22.2	3.6	4.4	11.1	9.7	3.6	2.1	3.7	2.3	4.2	16.6	2.1
KEYBOARD	Score :	384	62	76	192	168	62	36	64	39	72	72	36
	Priority (%) :	27.3	4.4	5.4	13.6	11.9	4.4	2.6	4.5	2.8	5.1	5.1	2.6
SPRING FOIL	Score :	96	62	76	192	62	62	36	64	39	72	72	36
	Priority (%) :	9.5	6.1	7.5	19.0	6.1	6.1	3.6	6.3	3.8	7.1	7.1	3.6
PLASTIC COVER	Score :	384	62	76	192	62	62	36	64	39	72	72	36
	Priority (%) :	29.5	4.8	5.8	14.8	4.8	4.8	2.8	4.9	3.0	5.5	5.5	2.8
DOME FOIL	Score :	96	62	76	192	62	62	36	64	39	72	72	36
	Priority (%) :	9.5	6.1	7.5	19.0	6.1	6.1	3.6	6.3	3.8	7.1	7.1	3.6
PCB ASSY	Score :	96	62	76	192	168	62	72	64	39	72	72	36
	Priority (%) :	7.2	4.6	5.7	14.4	12.6	4.6	5.4	4.8	2.9	5.4	5.4	2.7
SCREWS	Score :	96	62	76	192	168	62	36	64	39	72	72	36
	Priority (%) :	8.6	5.5	6.8	17.2	15.0	5.5	3.2	5.7	3.5	6.4	6.4	3.2
REAR COVER	Score :	96	62	76	192	62	62	36	64	39	72	72	36
	Priority (%) :	9.5	6.1	7.5	19.0	6.1	6.1	3.6	6.3	3.8	7.1	7.1	3.6

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Figure (6.5) The Design Analysis Report of the Calculator for Robotic Assembly

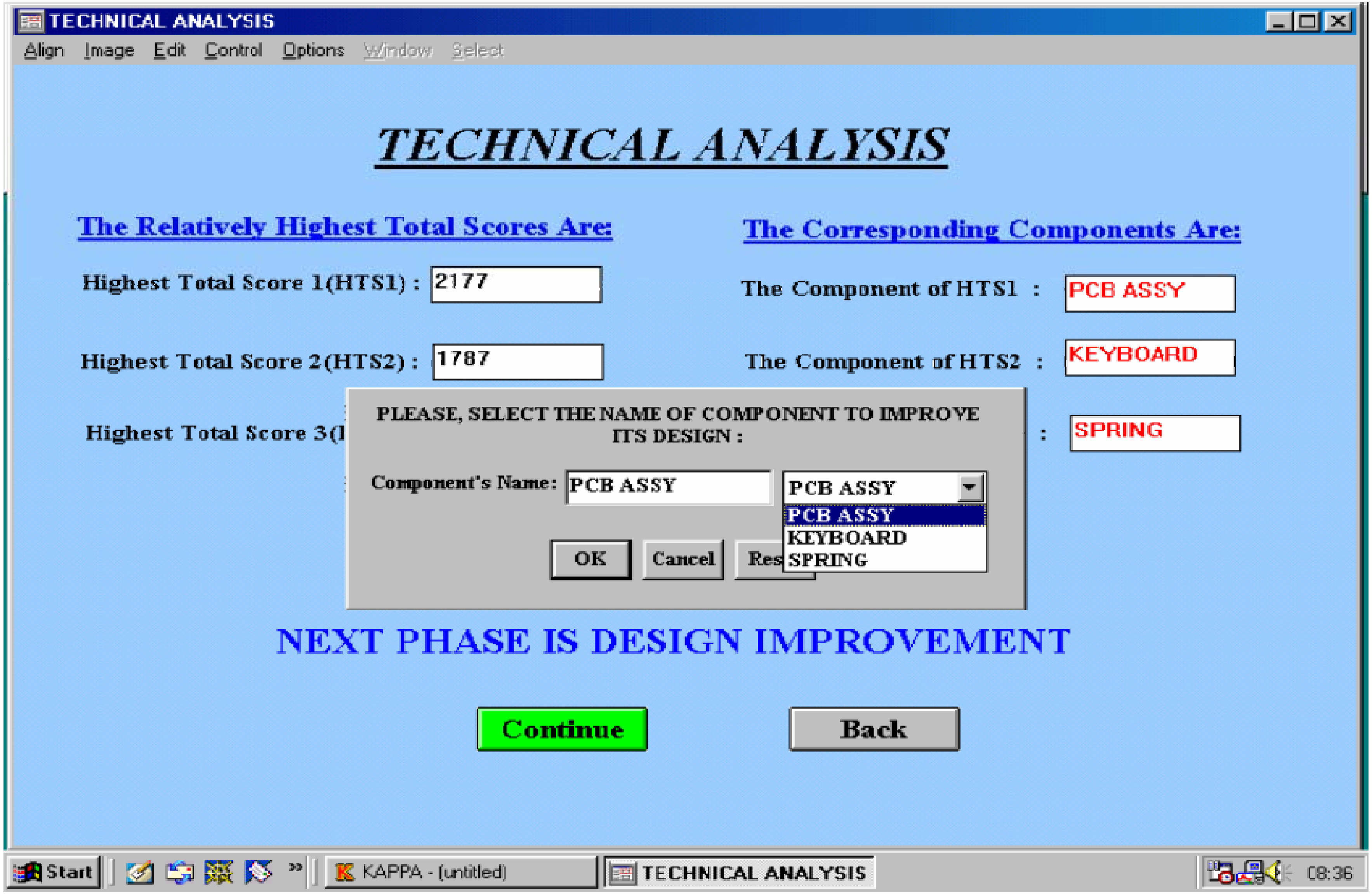


Figure (6.6) The Candidate Components for Redesign

6.3.4 Redesign Suggestions for Ease of Assembly

The primary aim of the design modifications is to improve the design of the product to make it more suited to automated assembly. The redesign considered both the product design and the assembly operations. The design modifications were carried out in two levels, the product structure level and the product components level.

It is important to adapt the design of the product to utilise automated assembly. For this reason, a series of suggestions for modifications the design without any compromise to its function, were proposed with the purpose of simplifying the assembly process. The redesign stage focuses particularly on the three components that have been mentioned in previous section. The Printed Circuit Board (PCB) and front assembly were examined to illustrate the ability of the system to provide redesign suggestions. Figure (6.7) illustrates the system output showing the various properties of PCB component which must be considered for redesign. These properties were component symmetry, alignment difficulty, insertion difficulty, and composing movement. For the composing movement, three motions namely tilting, moving, and snapping, are required for insertion of the PCB onto the front cover (see Figure (6.8)). This is because of the bad design of the snaps. The PCB could be snapped easily by a human operator, but would involve complicated motions for a robot (see Figure (6.8)). Therefore, the snaps at the keyboard area of the front assembly are redesigned to accommodate only one motion for insertion as shown in Figure (6.9).

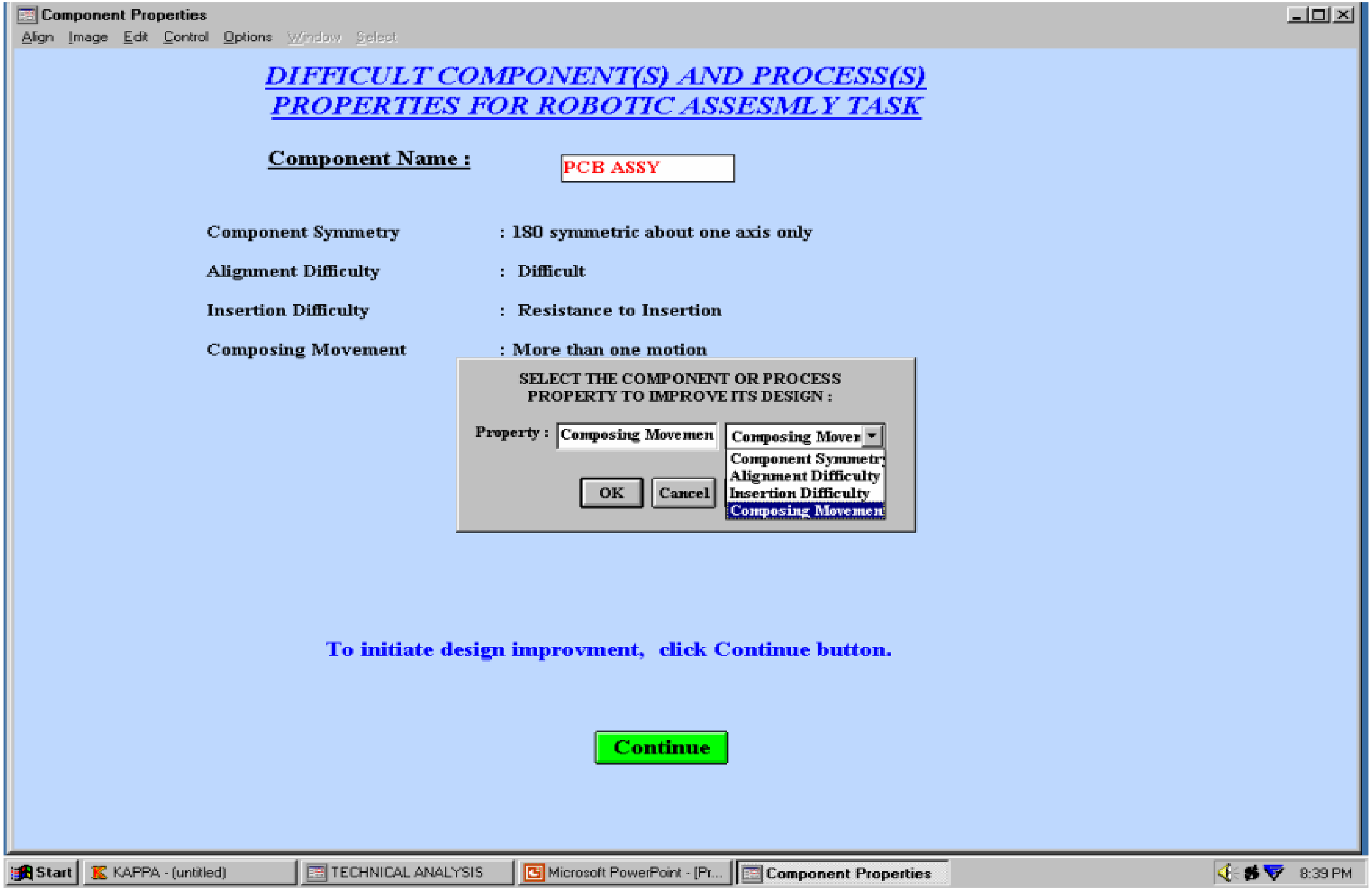


Figure (6.7) The System Result Showing the Various Properties of PCB Component, Which Must be considered for Redesign

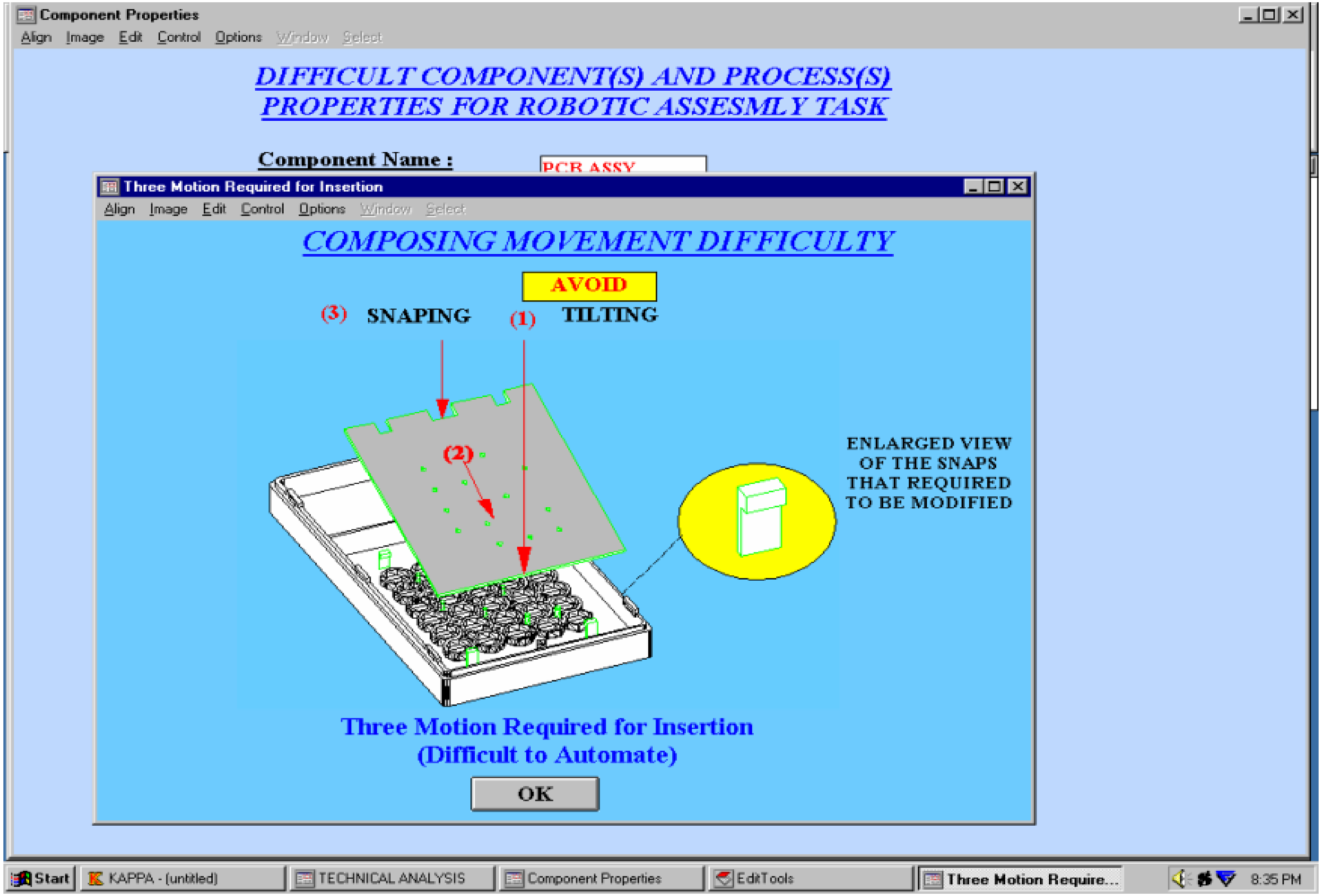


Figure (6.8) The Three Motions Required for Insertion (Difficult to Automate)

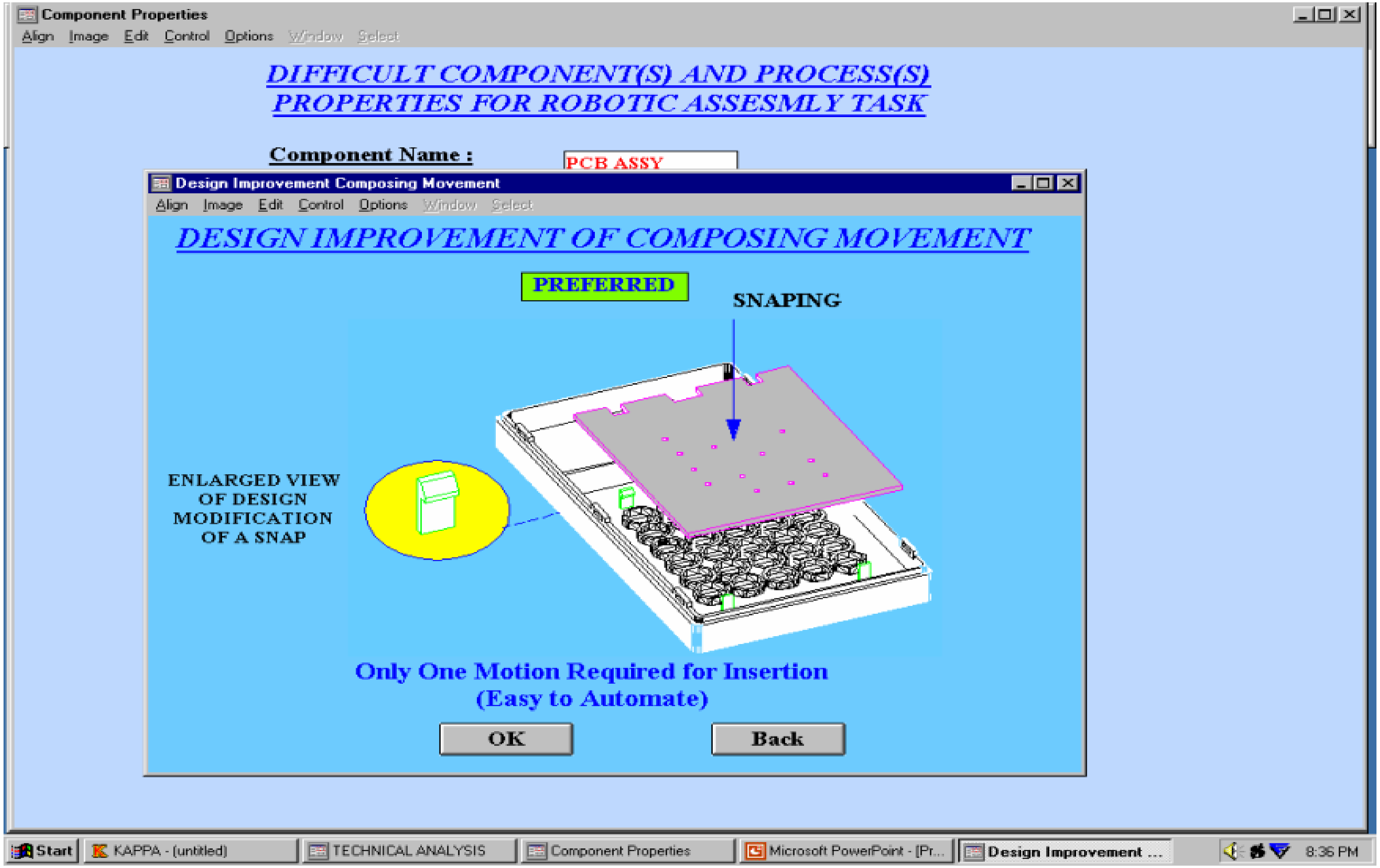


Figure (6.9) One Motion Required for insertion (Easy to Automate)

6.3.5 Cost Estimation using Robotic Assembly

The objective here is to estimate the assembly cost of the product for the robotic assembly method. This is based on the procedures previously discussed in section 5.8.3.

After the appropriate assembly technique was selected, the system begins to estimate the cost of assembly by analysing the product design. The design analysis of the calculator's components, for ease of robotic assembly, was examined for the various assembly processes. These assembly processes, as shown in Figure (5.26), include the difficulty of component placement, direction of assembly and the difficulty of insertion of the components. Table (6.2) shows the product analysis for multi-station robot assembly.

For presenting a component to a robot, three presentation techniques are used. These are programmable feeder (PF), special purpose feeder (SF), or manually loaded magazine, pallet, or component tray (MG). The system requests the user to specify which of these methods should be used for each component in the product. Table (6.3) illustrates the component feeding method and the associated costs for the components in the calculator.

To estimate the costs for robotic assembly, it was necessary to have the total cost of robots, grippers and all the special purpose equipment. The following are the main specifications of the robot system that were input to the system and used to estimate the assembly cost in the present case study:

- *Cost of standard assembly robot with controls, sensors, etc.: £ 50,625*
- *Number of stations on the multi-station system: 5*
- *Standard gripper cost: £3125*
- *The robot basic operation time: 3 sec*
- *Cost of one station on free transfer machine including buffers and controls: £ 15625*
- *Cost of special work carriers associated with one station on a multi-station system: £ 3125*

Component No.	Component Name	Difficulty for placement A =Add but not finally secured B =Add and secured immediately C =Separate securing operation or manipulation, or reorientation, or addition of non-solid material	Insertion direction (If you choose C from the previous column, select A or B only) A= Using motion along or about the vertical axis B = Using motion along or about a non vertical axis C = Involving motions along or about more than one axis	Insertion difficulty (If you choose A or B from the third column) A =Negligible resistance to insertion B = resistance to insertion	Gripper Type (If you choose A from the previous column) A = Standard gripper B = Special gripper	Holding down (If you choose A from the third column) A = No holding down B = Temporary holding or clamping required	(If you choose B from the third column) A= Snap or push fit B=Push and twist or other simple manipulation C= Snap or push fit or simple manipulation D= Screwing or nut running	Aligning difficulty (If you choose A or B from the third column) A = Self aligning B = Not easy to aligning	Mechanical fastening with simple motion (If you choose C from the third column) A=Negligible resistance to fastening B =Low resistance to fastening	A= Snap, push or twist B= Screw or nut tighten
11	Front Assy	A	A	A	B	A	-	A	-	-
10	Adapter End	B	A	A	A	A	A	A	-	A
9	Spring	A	A	A	B	B	-	A	-	-
8	Keyboard	A	A	A	B	A	-	A	-	A
7	Spring Foil	A	A	A	B	A	-	A	-	-
6	Plastic Cover	A	A	A	B	A	-	A	-	-
5	Dome Foil	A	A	A	B	A	-	A	-	-
4	PCB Assy	B	A	B	B	A	A	B	-	A
3	Screws	A	A	B	B	B	D	A	A	B
2	Rear Cover	B	A	B	B	A	A	B	-	A
1	Battery Cover	B	B	B	B	A	A	A	-	A

Table (6.2) Analysis of Scientific Calculator Components for Multi-Station Robot Assembly

COMP-ONENT NO	COMPONENT NAME	A	B	C	GENERAL-PURPOSE PORTION OF FEEDER COST, K£	SPECIAL-PURPOSE PORTION OF FEEDER OR MAGAZINE COST, K£
11	Front Assy.			C	-	0.625
10	Adapter End	A			2.187	0.313
9	Spring	A			2.187	0.313
8	Keyboard	A			2.187	0.313
7	Spring Foil	A			2.187	0.313
6	Plastic Cover	A			2.187	0.313
5	Dome Foil	A			2.187	0.313
4	PCB Assy			C	-	0.625
3	Screws		B		0.937	2.187
2	Rear Cover			C	-	0.625
1	Battery Cover	A			2.187	0.625

Table Key:

A = Programmable feeder (double-belt feeder, multi-component feeder with or without vision, etc)

B = Special-purpose feeder (like a vibratory-bowel feeder)

C = Manually loaded magazine, pallet, or component trays.

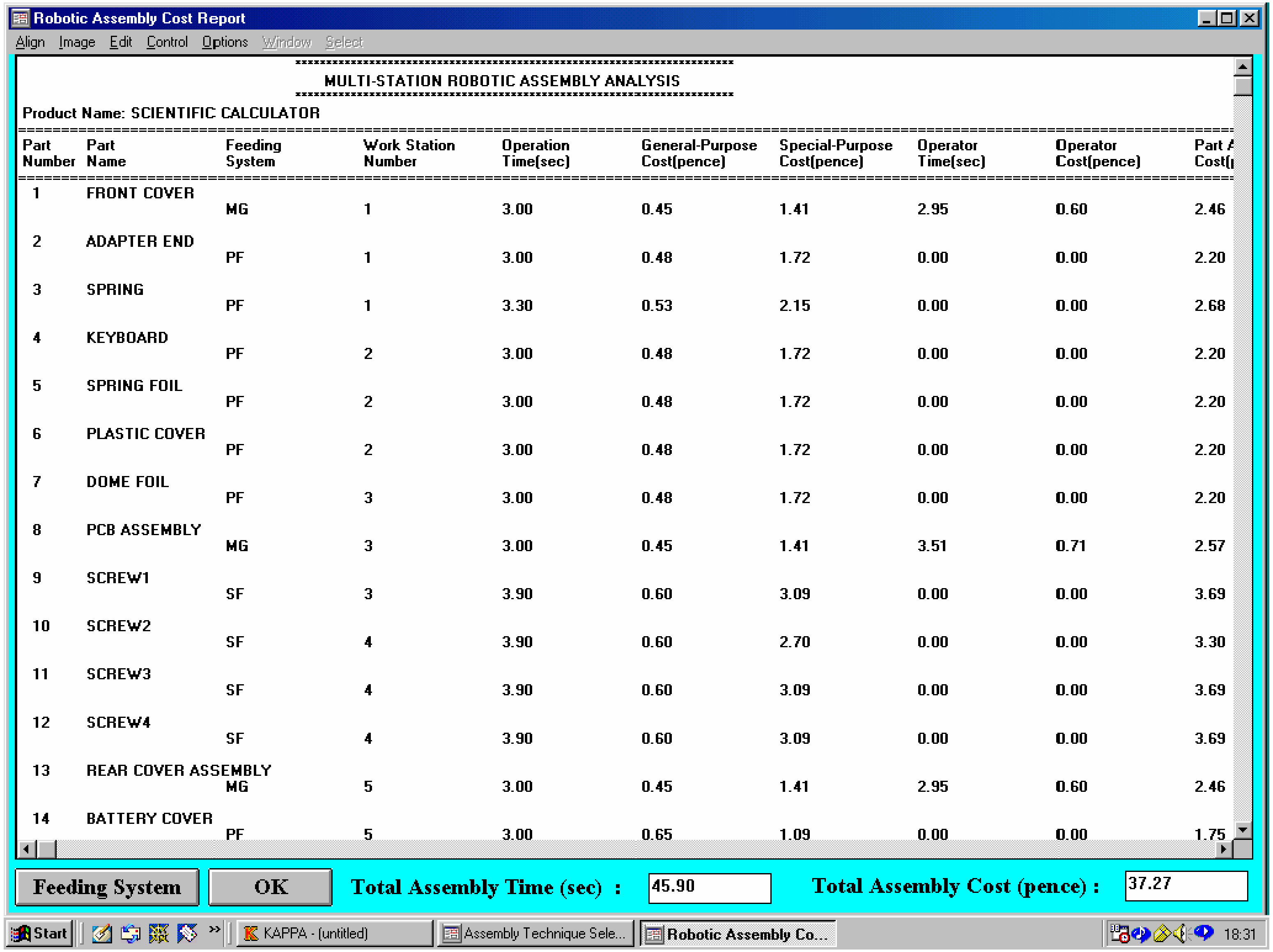
Table (6.3) Component Presentation Technique of Scientific Calculator to Robot

The multi-station assembly system cost estimation report for the scientific calculator was generated by the system and is illustrated in Figure (6.10). Summary of the analysis is shown below:

No. of work stations: 5

Assembly time : 45.90 seconds

Assembly cost : 37.27 pence



Robotic Assembly Cost Report

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MULTI-STATION ROBOTIC ASSEMBLY ANALYSIS

Product Name: SCIENTIFIC CALCULATOR

Part Number	Part Name	Feeding System	Work Station Number	Operation Time(sec)	General-Purpose Cost(pence)	Special-Purpose Cost(pence)	Operator Time(sec)	Operator Cost(pence)	Part A Cost(
1	FRONT COVER	MG	1	3.00	0.45	1.41	2.95	0.60	2.46
2	ADAPTER END	PF	1	3.00	0.48	1.72	0.00	0.00	2.20
3	SPRING	PF	1	3.30	0.53	2.15	0.00	0.00	2.68
4	KEYBOARD	PF	2	3.00	0.48	1.72	0.00	0.00	2.20
5	SPRING FOIL	PF	2	3.00	0.48	1.72	0.00	0.00	2.20
6	PLASTIC COVER	PF	2	3.00	0.48	1.72	0.00	0.00	2.20
7	DOME FOIL	PF	3	3.00	0.48	1.72	0.00	0.00	2.20
8	PCB ASSEMBLY	MG	3	3.00	0.45	1.41	3.51	0.71	2.57
9	SCREW1	SF	3	3.90	0.60	3.09	0.00	0.00	3.69
10	SCREW2	SF	4	3.90	0.60	2.70	0.00	0.00	3.30
11	SCREW3	SF	4	3.90	0.60	3.09	0.00	0.00	3.69
12	SCREW4	SF	4	3.90	0.60	3.09	0.00	0.00	3.69
13	REAR COVER ASSEMBLY	MG	5	3.00	0.45	1.41	2.95	0.60	2.46
14	BATTERY COVER	PF	5	3.00	0.65	1.09	0.00	0.00	1.75

Feeding System | OK | Total Assembly Time (sec) : 45.90 | Total Assembly Cost (pence) : 37.27

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Figure (6.10) Multi-station Robot Assembly Cost Estimation Report for the Present Case Study

6.4 Cost Estimation for Injection Moulded Components

6.4.1 Case Study 2 – Front Cover (Calculator)

In this study, the injection moulding process was considered for the manufacture of the front cover of the scientific calculator. Injection moulding has several advantages in the mass production of complex components. These include a direct path from resin to finished component, minimal finishing of the component, full automation and repeatability. This method of fabrication has replaced the need for conventional processes like machining in many application areas.

The procedure for estimating the cost of a product using this system, requires that the designer interacts with a CAD system to model the component and its features (see Figure (6.11)). Then the user should either specify the material to be used, based on certain criteria or select it from the CMS software. The necessary material data are retrieved by the system. Figure (6.12) illustrates the retrieved data for the calculator’s front cover and the material used.

The system allows the user to enter data related to the product and its production parameters. The data entered include the batch size, production volume and component’s characteristics. The production parameters for the present case study are:

Component name	*: FRONT COVER (CALCULATOR)*
Average wall thickness (mm)	*: 3*
Batch size	*: 4,000*
Annual Production volume	*: 250,000*

A mould basically has two sets of components, the cavities and cores, and the base in which the cavities and cores are mounted. A set of default data, such as machine set up and mould base data are provided in order to calculate the operation rates of the injection moulding machine and the size of the mould base. The user can alter the default values to suit his/her own working conditions.

The default information used in the present case study are shown below:

Mould default data

No. of base plates	*: 3*
Clearance between cavities (mm)	*: 50*
Clearance between cavity and plate edge (mm)	*: 50*

Default input data

No. of operators	*:1*
Machine set up time (hr)	*: 2*
Annual labour cost (£)	*: 14,625*
Working hours per day	*: 8*
Working days per week	*: 5*
Working weeks per year	*: 48*
No. of shifts per day	*: 3*
Machine payback (years)	*: 3.5*
Production yield	*: 0.9*

The output provides the material, the processing, and the tooling costs as shown in Figure (6.13). The total estimated cost of producing the component, provided by the system, is £0.195. This figure deviates from the actual manufacturing cost by 12%. The reason is that the system is developed to provide the user with a design for cost-effectiveness.

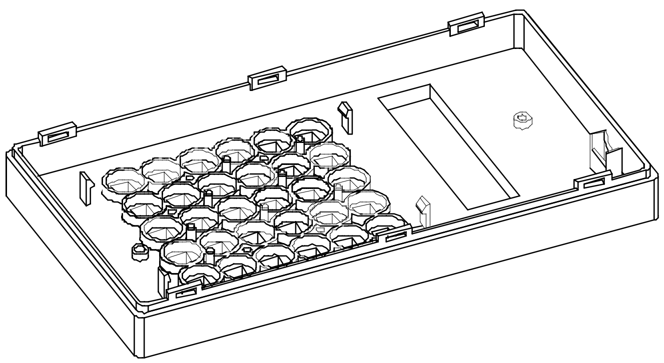


Figure (6.11) Solid Modelling Representation of Front Cover of a Scientific Calculator

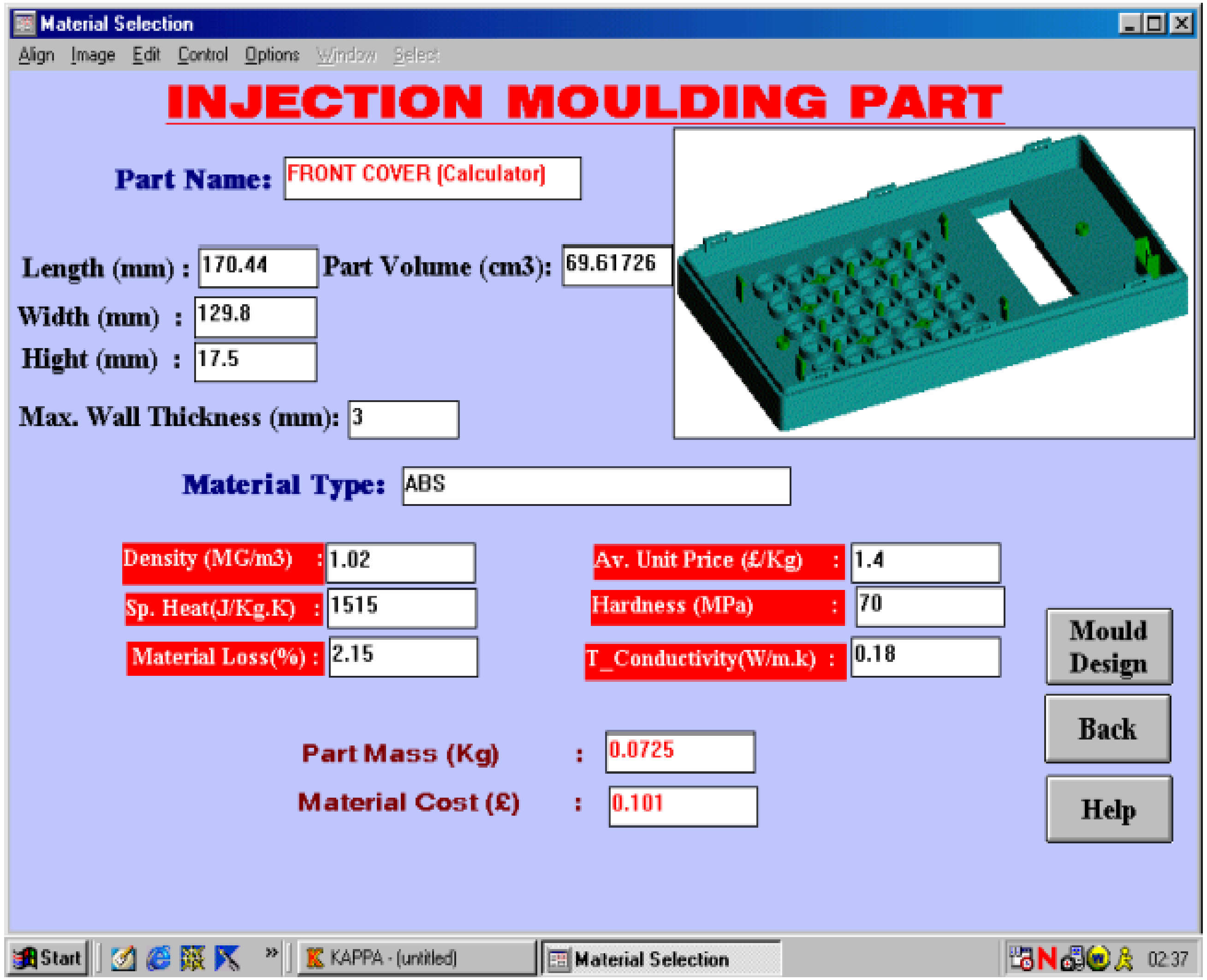


Figure (6.12) Component parameters and material properties retrieved by the proposed system

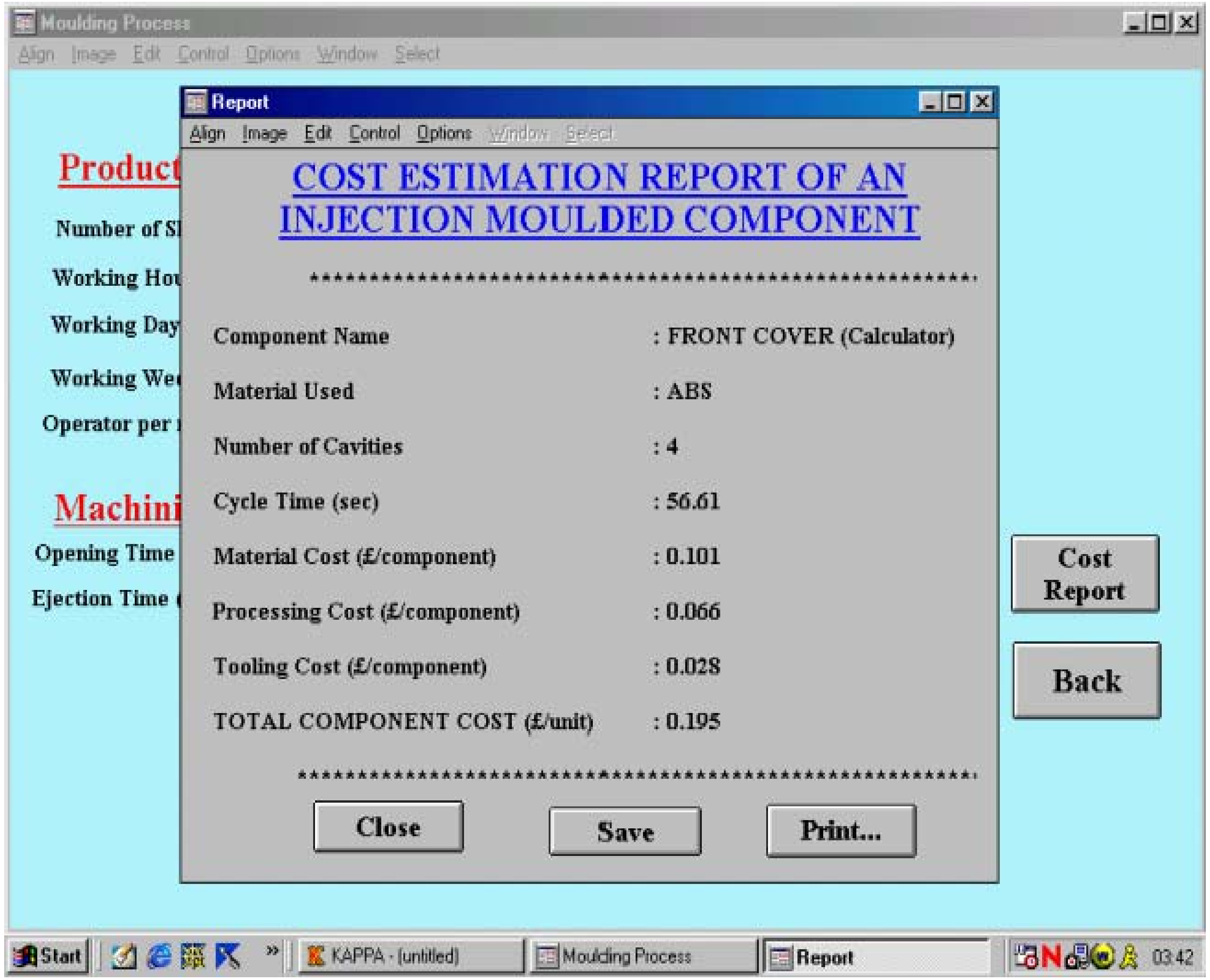


Figure (6.13) Typical Screenshot of the Cost Estimation Report of the Front Cover (Scientific Calculator)

6.4.2 *Case Study 3 – Telephone Handset*

Analysis of the costs for producing a telephone handset was chosen for confirmation of the capability of the developed system to generate reliable cost. The user commenced the cost estimation process by entering the data relating to the product and production parameters. The data entered include batch size, production volume and component characteristics. The production parameters for the present case study were:

Component name : *PHONE HANDSET*
Average wall thickness (mm) : *3*
Batch size : *4,000*
Annual Production volume : *90,000*

A 3-D solid model of the component was generated on a CAD system as shown Figure (6.14). Then the user should either specify the material or select the material from CMS software. In the present case study, the user interacted with the CMS software to choose candidate material for producing the component. Based on a set of constraints such as product functionality, the type of manufacturing process and material properties, CMS recommended Acrylo-butadiene-styrene (ABS) as the appropriate material. The necessary material data were retrieved by the proposed system. The retrieved data from the database of the CAD system and the CMS is shown in Figure (6.15):

Component envelope length (mm) : *203.17*
Component envelope width (mm) : *57.20*
Component envelope hight (mm) : *40.77*
Component volume (cm^3) : *85.684*
Material used : *ABS*
Average material unit price (£/kg): *1.4*
Material density (Mg/m^3) : *1.02*
Material loss (%) : *2.15*
Hardness (Mpa) : *70*

The operation rates of the injection moulding machine and the size of the mould base were calculated based on set of default data such as machine set up and mould base data. The default values can be changed by users to accommodate their own working conditions. The default machining and production parameters are shown in Figure (6.16).

The output cost estimation report generated by the developed system, included the total cycle time, the material cost, the component processing cost and the tooling cost as shown in Figure (6.17).

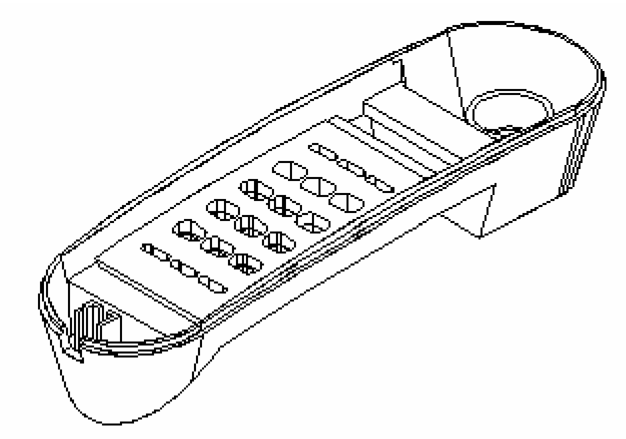


Figure (6.14) A 3-D Solid Model of a Phone Handset

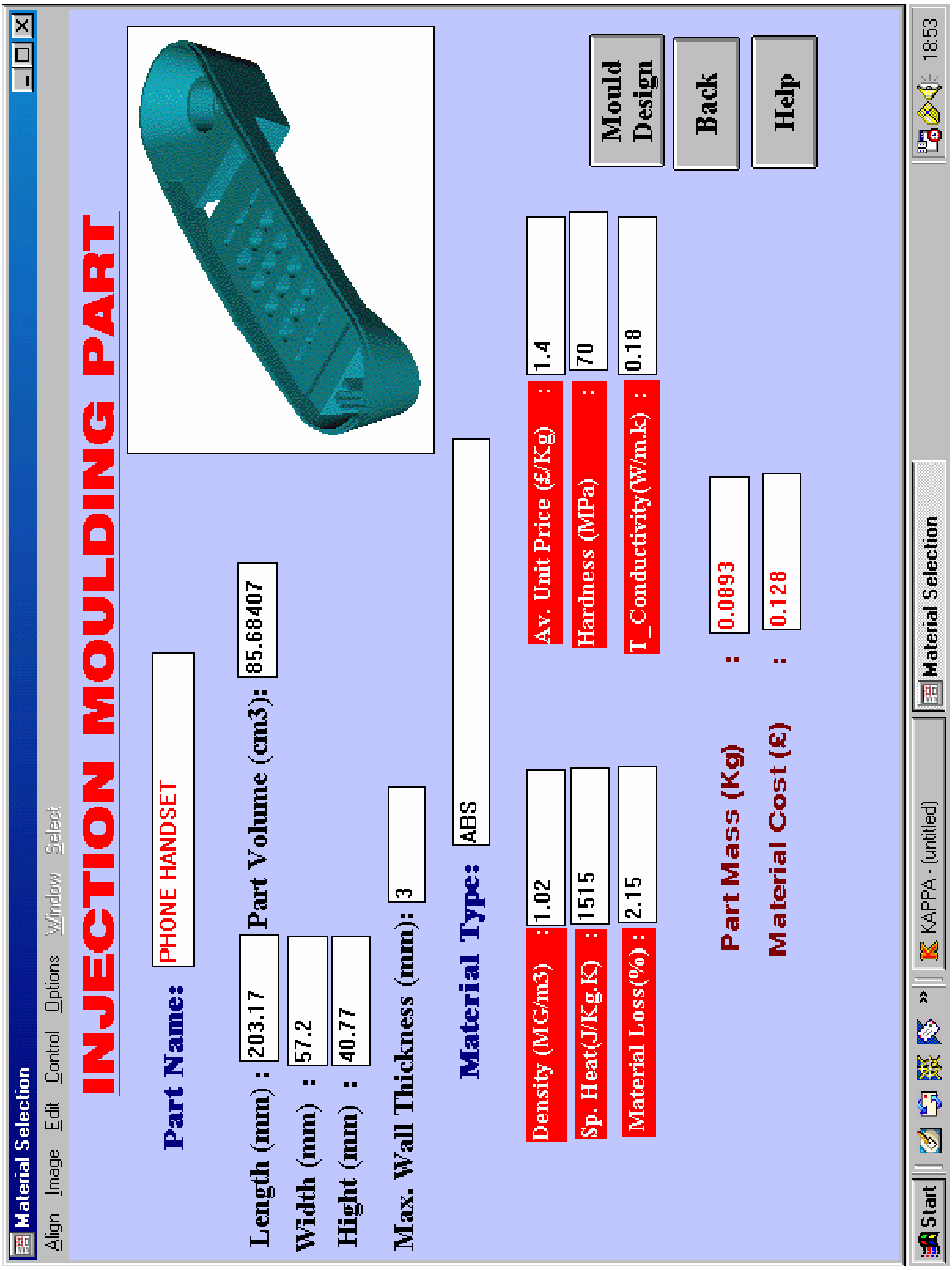


Figure (6.15) Component Parameters and Material Properties Retrieved by the Developed System

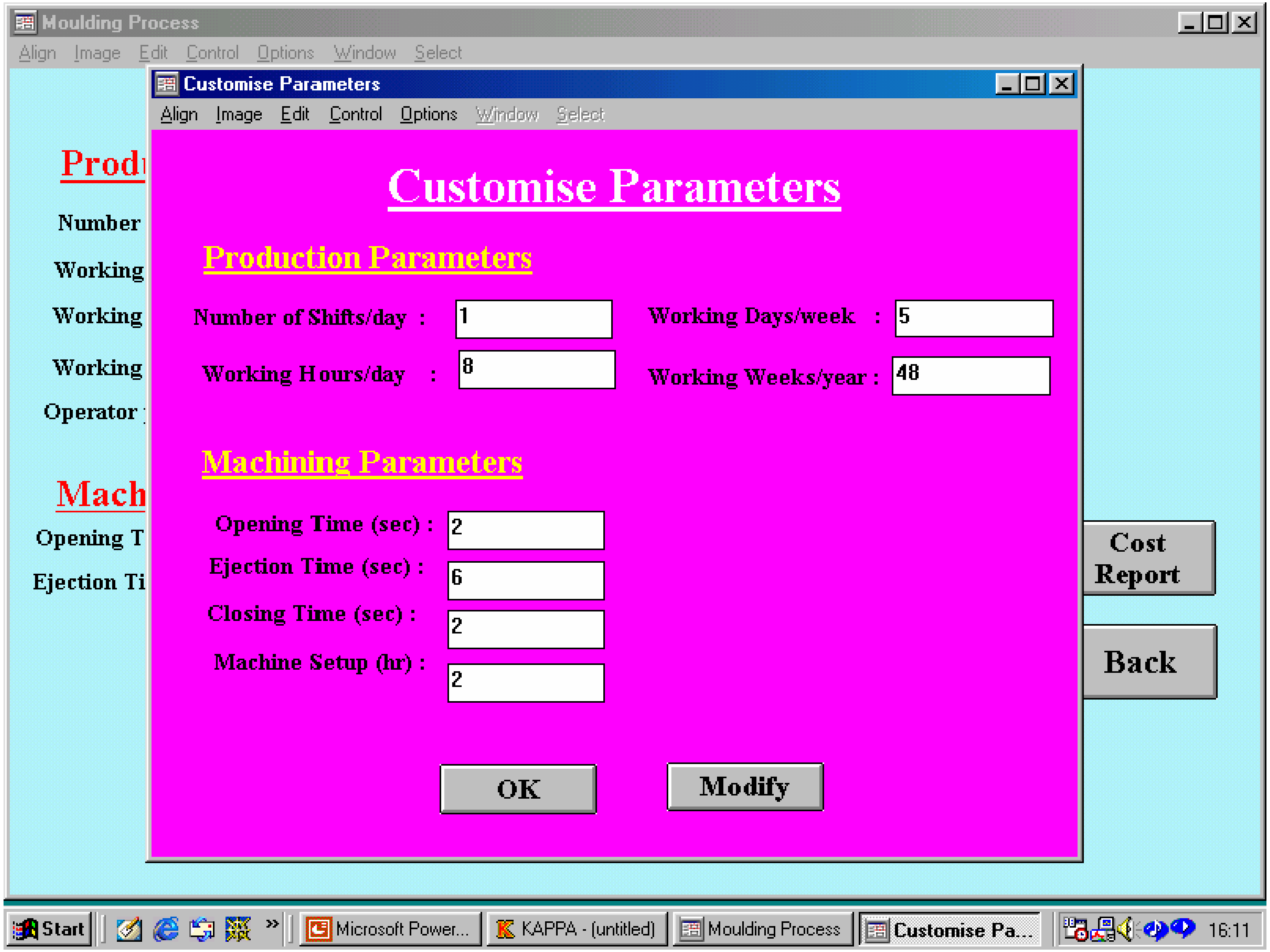


Figure (6.16) Default Production and Machining Parameters

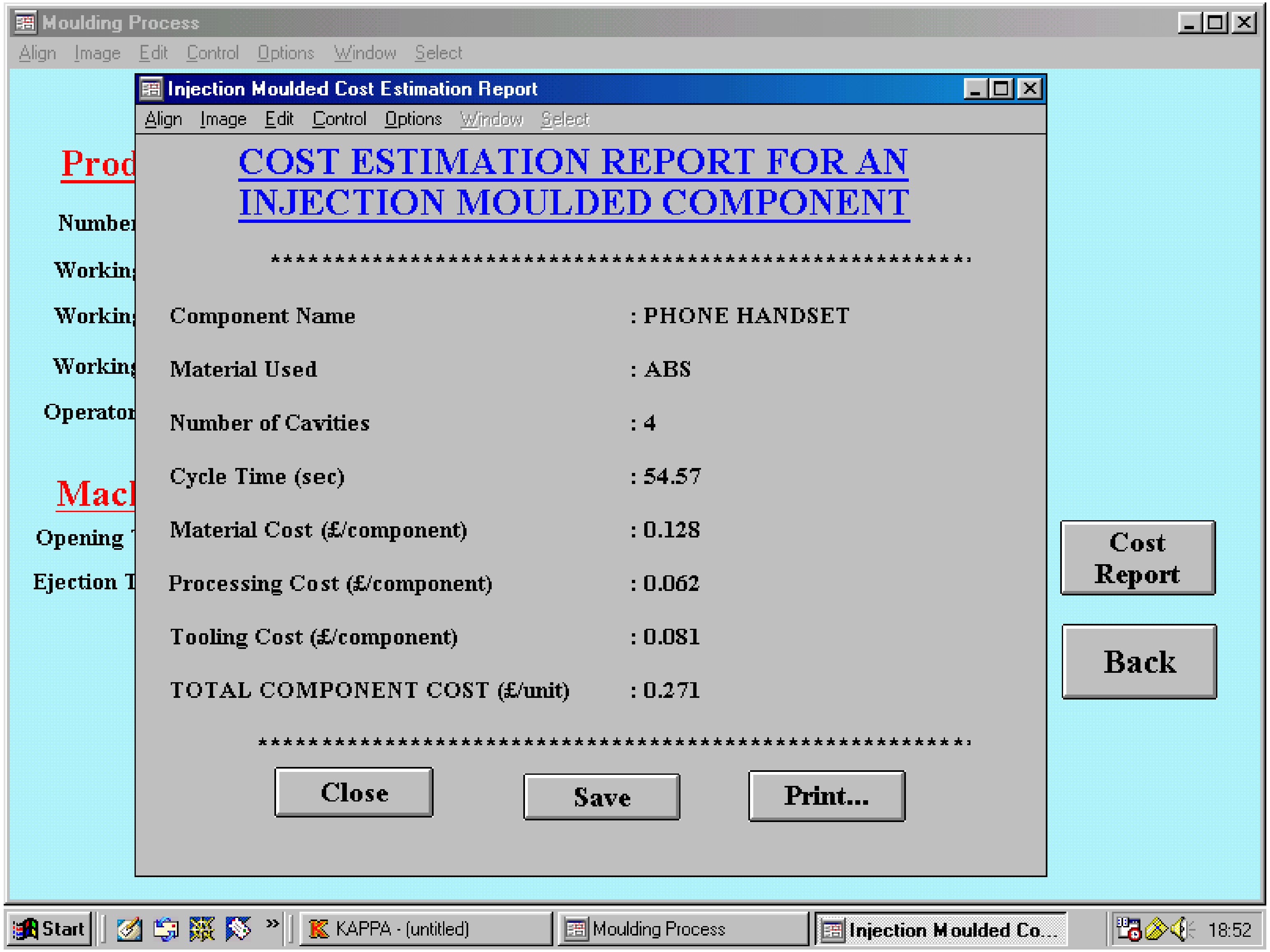


Figure (6.17) Cost Estimation Report of the Telephone Handset

6.5 Cost Modelling of Machined Components

For cost effective design of a machined component, the developed system has the capability: (1) to select a material and estimate the material cost, (2) to recommend the machining processes and parameters, based on a set of design and production parameters, (3) to estimate the manufacturing cost as well as the machining and non-productive times. In order to demonstrate these capabilities, two real-life machined components have been chosen as case studies. To determine the accuracy of the cost estimation by the system, a machined component, a Transmission-Transfer Block, was machined using a CNC milling machine in the workshops at De-Montfort University.

6.5.1 Case Study 4 – Transmission-Transfer Block

Before proceeding with the cost estimation, the designer must create a solid model of the design, in order to extract the envelope dimension of the component and its volume from the CAD system. A geometric representation and the 3-views of the machined component are shown in Figure (6.18). The component contains five different kinds of features, two through rectangular slots, sixteen blind holes, four steps with round corners, four through holes, one threading hole and ten rectangular pockets with round corners. Based on the functionality of the component, the user again has to specify his/her own material or select a material from CMS. The properties of the selected material are saved as a data file so they can be extracted by the system. The material cost is estimated based on the volume of the blank used. The estimated processing time, for each feature, is based on information including the material used, process planning, the values of the defined parameters of each feature, and the specified surface finish of each face of a feature. The manufacturing criteria considered for milling and drilling operations performed on a CNC milling machine. In addition, non-traditional machining techniques such as electrode discharge machining (EDM) and laser beam machining (LBM) have been taken into account for producing the features that cannot be manufactured by traditional machines. The total cost rate (C_T) of the CNC machine was obtained from the following equation:

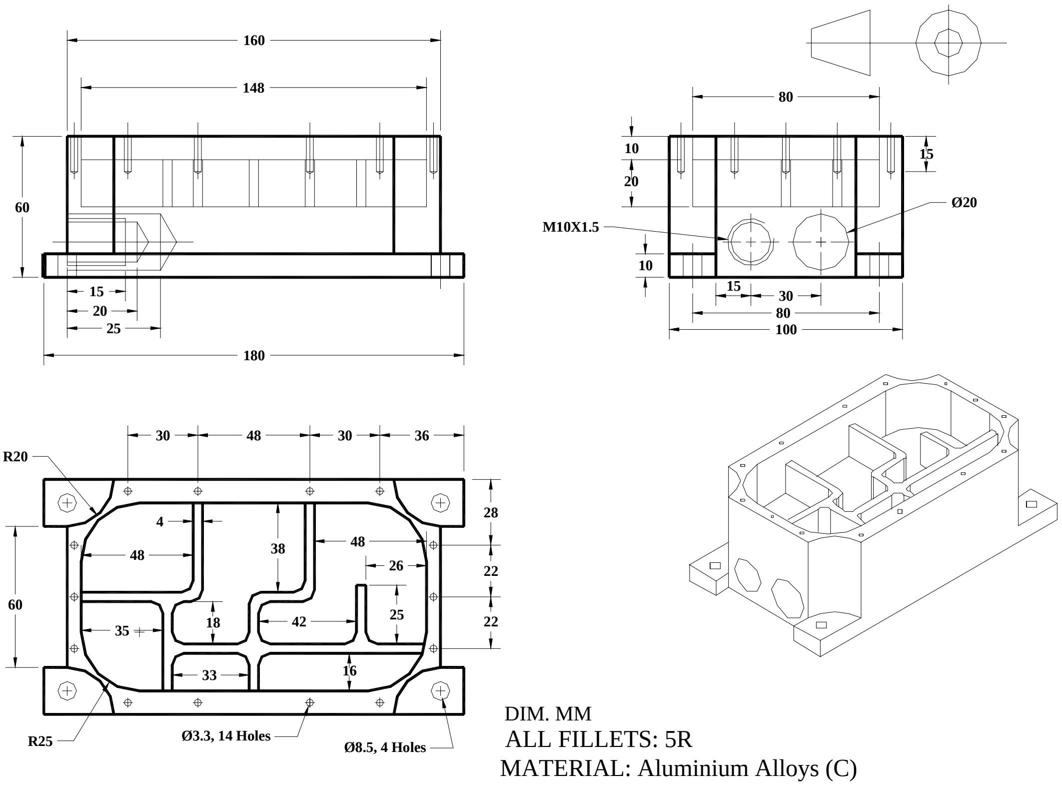


Figure (6.18) Geometric Representation and the 3-Views of the Transmission Transfer Block

$$C_T = C_L + C_M \qquad (6.\ 1)$$

Where:

C_L = Labour cost rate (£/hr),

C_M = Machine cost rate (£/hr).

The labour cost rate is made up of the direct labour wage rate and overheads. The machine cost rate includes the machine depreciation rate and the machine overheads. The depreciation rate is calculated based on the working hours per year and the amortisation period. The machine overhead includes the cost of routine maintenance, the cost of unexpected breakdowns and services and the cost of the factory space used. These two cost components are explained in the following:

1. Labour cost rate, C_L

   Annual labour cost
   including overhead = £ 14,625
   Working hours per day = 8
   Working days per week = 5
   Working weeks per year = 48

$$C_L = \frac{AnnualLabourCost}{WorkingHoursPerYear} = \frac{14625}{8 \times 5 \times 48}$$

= 7.62 £/hr

2. Machine cost rate, C_M

   Equipment cost = £151,473
   Amortisation period = 8 years
   Overhead = 30%
   Working hours per year are the same as above.

   C_M = Machine depreciation rate + Machine overhead

$$= \left[\frac{151473}{8 \times 8 \times 5 \times 48}\right] \times 1.3$$

= 12.82 £/hr

By substituting the costs components into Equation (6.1) gives:

C_T = 20.44 £/hr

The total machining cost rate for EDM and LBM were obtained from Yeo et. al (1997). The system displays the default parameters for the production and machine parameters and are based on the user's response, the system then estimates the unit time cost, non-production time and set up time accordingly. These are shown in Figure (6.19). The production parameters include total annual labour cost and working hours per year. The machine parameters include machine cost, machine overheads, and the amortisation period.

Figure (6.20) illustrates the cost estimation report prepared by the system for the present case study. A feature-by-feature cost estimation, in the cost report, is very useful for the user as it indicates features with high processing cost. Consequently, the user can adjust the design based on the results.

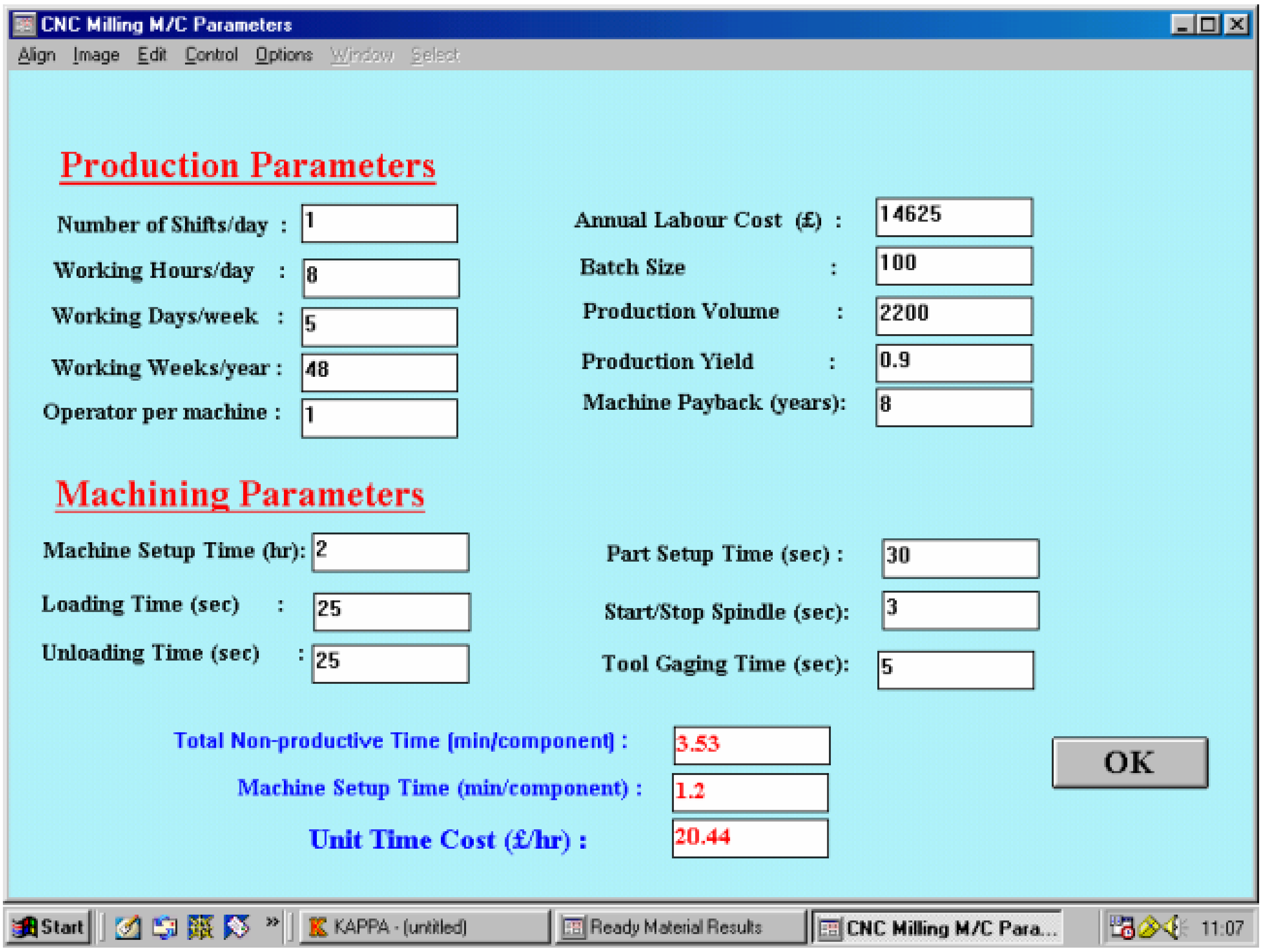
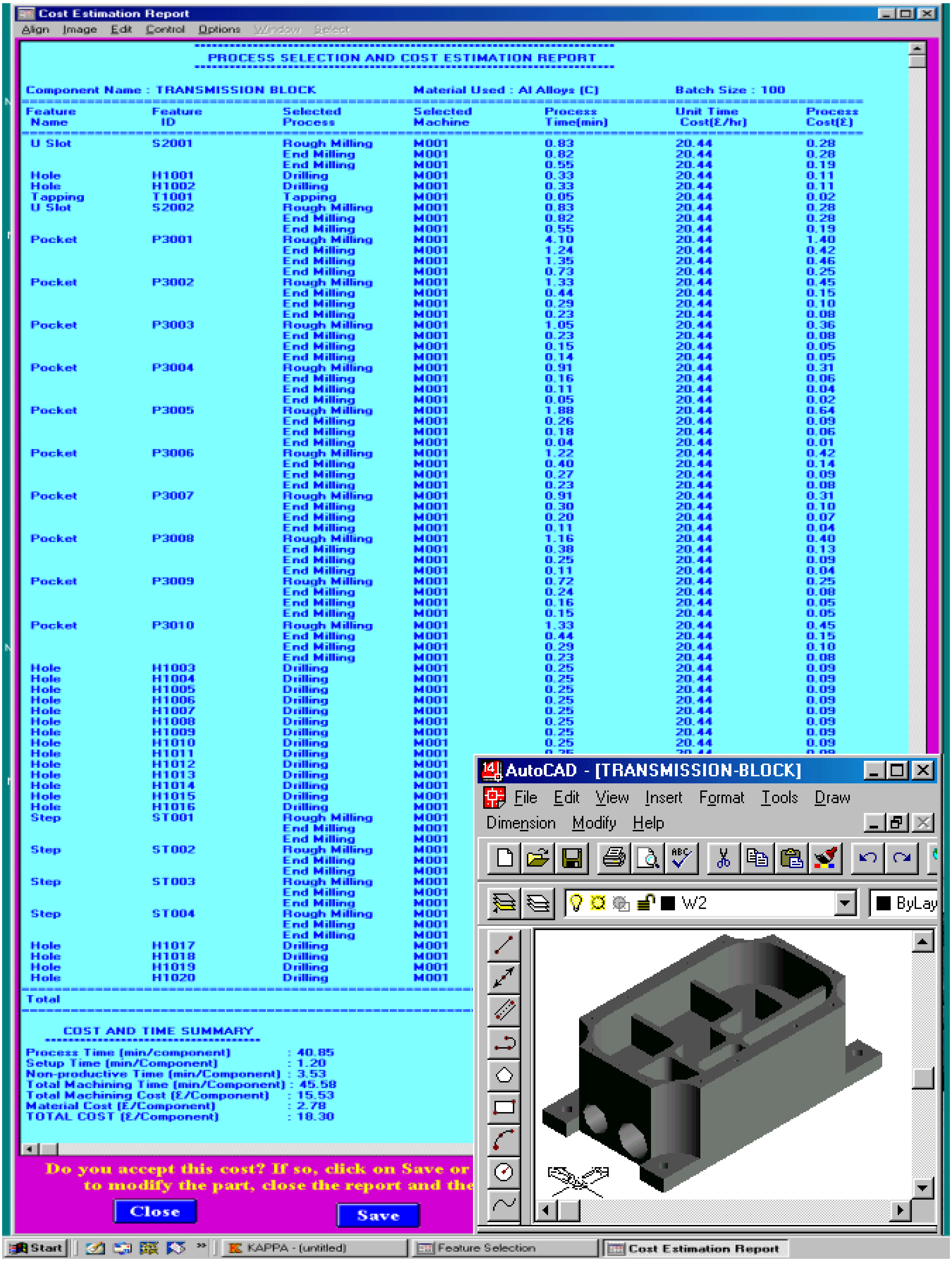


Figure (6.19) Production and Machine Parameters for CNC Milling Machine



PROCESS SELECTION AND COST ESTIMATION REPORT

Component Name : TRANSMISSION BLOCK   Material Used : Al Alloys (C)   Batch Size : 100

Feature Name	Feature ID	Selected Process	Selected Machine	Process Time(min)	Unit Time Cost(£/hr)	Process Cost(£)
U Slot	S2001	Rough Milling	M001	0.83	20.44	0.28
		End Milling	M001	0.82	20.44	0.28
		End Milling	M001	0.55	20.44	0.19
Hole	H1001	Drilling	M001	0.33	20.44	0.11
Hole	H1002	Drilling	M001	0.33	20.44	0.11
Tapping	T1001	Tapping	M001	0.05	20.44	0.02
U Slot	S2002	Rough Milling	M001	0.83	20.44	0.28
		End Milling	M001	0.82	20.44	0.28
		End Milling	M001	0.55	20.44	0.19
Pocket	P3001	Rough Milling	M001	4.10	20.44	1.40
		End Milling	M001	1.24	20.44	0.42
		End Milling	M001	1.35	20.44	0.46
		End Milling	M001	0.73	20.44	0.25
Pocket	P3002	Rough Milling	M001	1.33	20.44	0.45
		End Milling	M001	0.44	20.44	0.15
		End Milling	M001	0.29	20.44	0.10
		End Milling	M001	0.23	20.44	0.08
Pocket	P3003	Rough Milling	M001	1.05	20.44	0.36
		End Milling	M001	0.23	20.44	0.08
		End Milling	M001	0.15	20.44	0.05
		End Milling	M001	0.14	20.44	0.05
Pocket	P3004	Rough Milling	M001	0.91	20.44	0.31
		End Milling	M001	0.16	20.44	0.06
		End Milling	M001	0.11	20.44	0.04
		End Milling	M001	0.05	20.44	0.02
Pocket	P3005	Rough Milling	M001	1.88	20.44	0.64
		End Milling	M001	0.26	20.44	0.09
		End Milling	M001	0.18	20.44	0.06
		End Milling	M001	0.04	20.44	0.01
Pocket	P3006	Rough Milling	M001	1.22	20.44	0.42
		End Milling	M001	0.40	20.44	0.14
		End Milling	M001	0.27	20.44	0.09
		End Milling	M001	0.23	20.44	0.08
Pocket	P3007	Rough Milling	M001	0.91	20.44	0.31
		End Milling	M001	0.30	20.44	0.10
		End Milling	M001	0.20	20.44	0.07
		End Milling	M001	0.11	20.44	0.04
Pocket	P3008	Rough Milling	M001	1.16	20.44	0.40
		End Milling	M001	0.38	20.44	0.13
		End Milling	M001	0.25	20.44	0.09
		End Milling	M001	0.11	20.44	0.04
Pocket	P3009	Rough Milling	M001	0.72	20.44	0.25
		End Milling	M001	0.24	20.44	0.08
		End Milling	M001	0.16	20.44	0.05
		End Milling	M001	0.15	20.44	0.05
Pocket	P3010	Rough Milling	M001	1.33	20.44	0.45
		End Milling	M001	0.44	20.44	0.15
		End Milling	M001	0.29	20.44	0.10
		End Milling	M001	0.23	20.44	0.08
Hole	H1003	Drilling	M001	0.25	20.44	0.09
Hole	H1004	Drilling	M001	0.25	20.44	0.09
Hole	H1005	Drilling	M001	0.25	20.44	0.09
Hole	H1006	Drilling	M001	0.25	20.44	0.09
Hole	H1007	Drilling	M001	0.25	20.44	0.09
Hole	H1008	Drilling	M001	0.25	20.44	0.09
Hole	H1009	Drilling	M001	0.25	20.44	0.09
Hole	H1010	Drilling	M001	0.25	20.44	0.09
Hole	H1011	Drilling	M001			
Hole	H1012	Drilling	M001			
Hole	H1013	Drilling	M001			
Hole	H1014	Drilling	M001			
Hole	H1015	Drilling	M001			
Hole	H1016	Drilling	M001			
Step	ST001	Rough Milling	M001			
		End Milling	M001			
		End Milling	M001			
Step	ST002	Rough Milling	M001			
		End Milling	M001			
		End Milling	M001			
Step	ST003	Rough Milling	M001			
		End Milling	M001			
		End Milling	M001			
Step	ST004	Rough Milling	M001			
		End Milling	M001			
		End Milling	M001			
Hole	H1017	Drilling	M001			
Hole	H1018	Drilling	M001			
Hole	H1019	Drilling	M001			
Hole	H1020	Drilling	M001			
Total						

COST AND TIME SUMMARY

Process Time (min/component) : 40.85
Setup Time (min/Component) : 1.20
Non-productive Time (min/Component) : 3.53
Total Machining Time (min/Component) : 45.58
Total Machining Cost (£/Component) : 15.53
Material Cost (£/Component) : 2.78
TOTAL COST (£/Component) : 18.30

Figure (6.20) The Cost Estimation Report Generated for the Present Case Study

6.5.1.1 Comparison of Estimated and Actual Costs

The system was validated through a real case study, where machining time and cost estimated by the system was compared with the machining time and cost using a CNC machine in the workshop (See Figure (6.21)). The comparison showed that the cost estimated was almost 10% less than the actual cost estimation since the system takes into consideration process optimisation, design alternatives, and design for assembly issues. This demonstrates the reliability of the developed system for cost estimation at early design stage

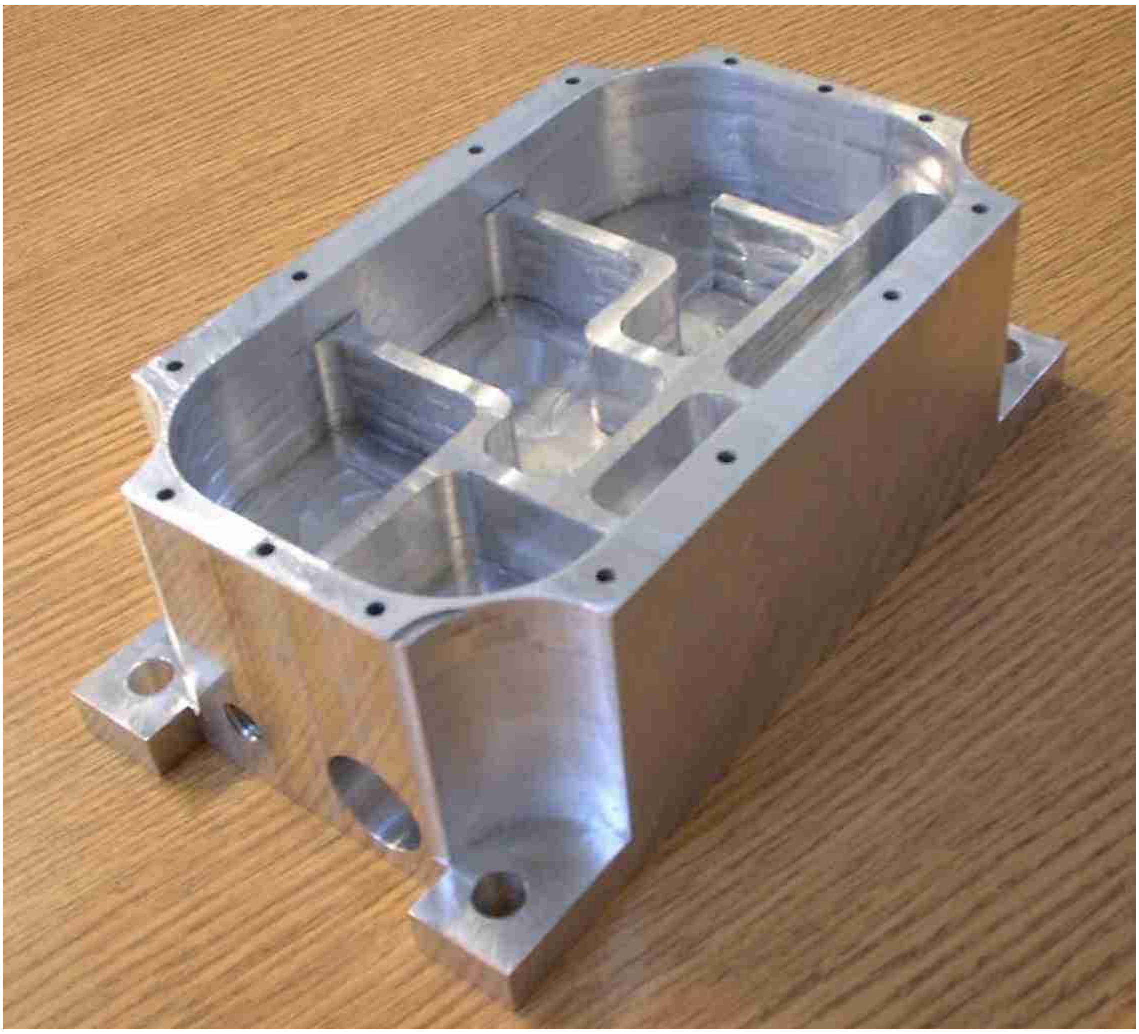


Figure (6.21) The Finished Component after machining

6.5.2 Case Study 5 - Socket

Here is another case study presented to validate the developed system. The solid model of a sample of a socket is shown in Figure (6.22). The component contains four different kinds of feature, two through slot, seven holes, four blind steps and two pockets with sharp corners. The designer starts the cost estimation process by entering the topological and geometrical attributes of the design model into the system.

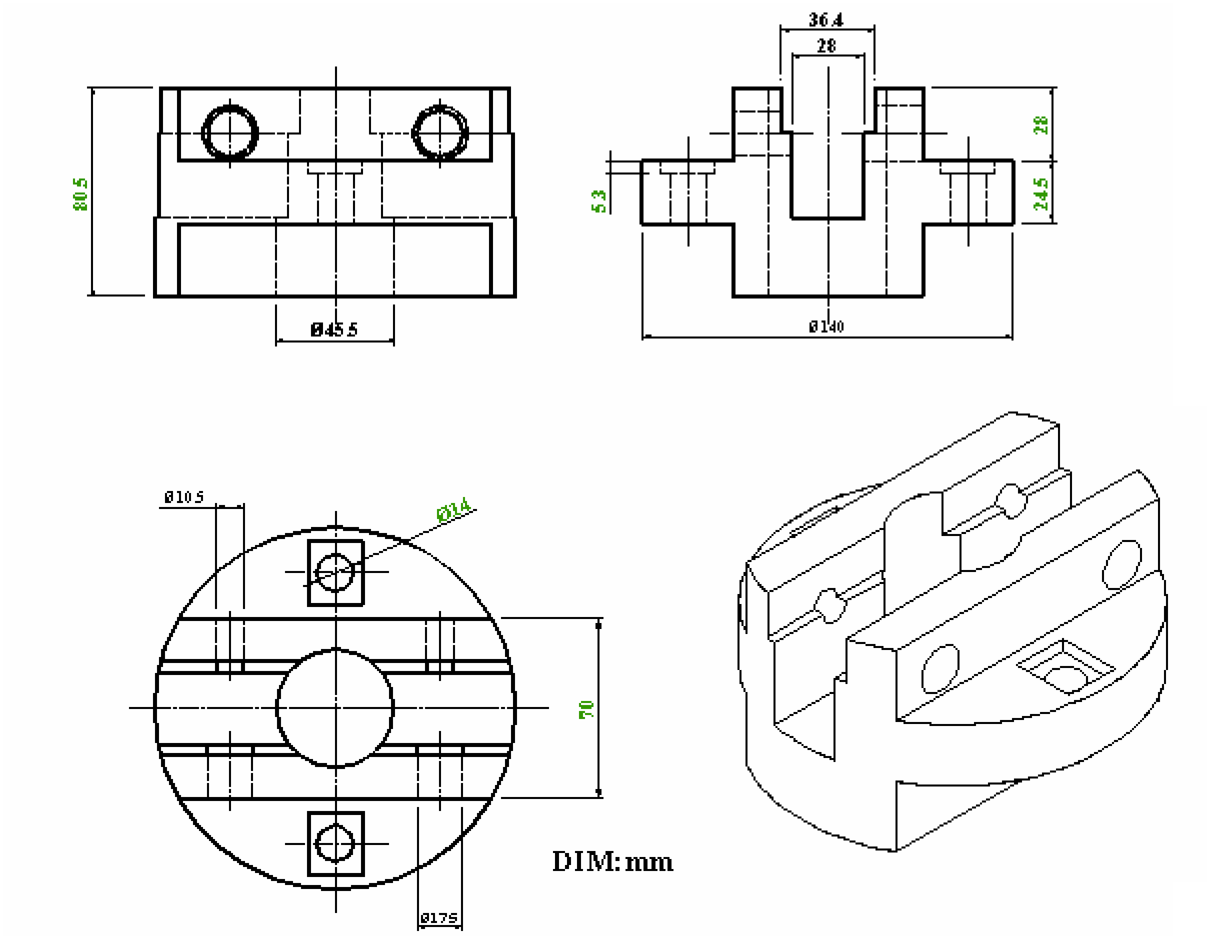


Figure (6.22) A Sample Machined Component (Socket)

In this case study, the user interacts with CMS to choose a suitable material for producing the component. The properties of the candidate material, in this example, low carbon steel, have been saved as a data file which can be retrieved by system. Typical material specifications as well as the component volume and the envelope dimensions as retrieved automatically by the system are shown in Table (6.4).

Defined Parameter	**Retrieved Data**
Component envelope length (mm)	140
Component envelope width (mm)	140
Component envelope height (mm)	80.5
Final component volume (cm^3)	595.86
Raw material component volume (cm^3)	1239.20
Material used	Low Carbon Steel
Average material unit price (£/kg)	0.361
Material density(Mg/m^3)	7.85
Thermal Conductivity (W/m.K)	51.5
Hardness (Mpa)*	1405

* The hardness unit used in CMS.

Table (6.4) The Retrieved Data of the Present Case Study by the System

The available manufacturing facilities such as machines, processes, shape capabilities, and cutting tools were provided by the user via the user interface, in order to accomplish the required analyses. The system selected the possible processes, for the features of the component subject to the criteria, which were included in the process selection rules, as explained in chapter 5. The available machining processes that were capable of producing the form features were selected. For example, a sharp pocket could be produced only by EDM.

When the process selection for the form features of the component were completed, the cutting tools were selected. The cutting tool selection based on the available cutting tools that provided by the user, the selected material, the type and dimensions of the form features, and the selected feasible process for the component features. The system displayed the recommendations for the machining parameters, for manufacturing a slot in a system window as illustrated in Figure (6.24). The machining parameters included cutting tool, type and depth of cut.

Figure (6.23) illustrates the system’s recommendations for the present case study. One of the holes was found to be of a non-standard size so the system provided the user with an alternative cost effective hole size. The system displayed the recommendations which enabled the user to modify the design feature. The system found that the pockets had sharp inside corners, so could only be machined using the EDM process. The user was warned that this feature might lead to a sharp increase in the machining cost. The system provided recommendation to eliminate this problem. However the user accepted the machining cost, for this feature, based on the functionality of the component.

The cost estimation report generated by the system for the present case study is shown in Figure (6.25). The report has been designed to display, the feature name and its ID, the selected process, the assigned machine and its total cost rate, the estimated processing time and cost for producing the component features. Finally, the system summarised the total processing time, set-up time, non-productive time, the total machining time, material cost, machining cost, and the total component cost.

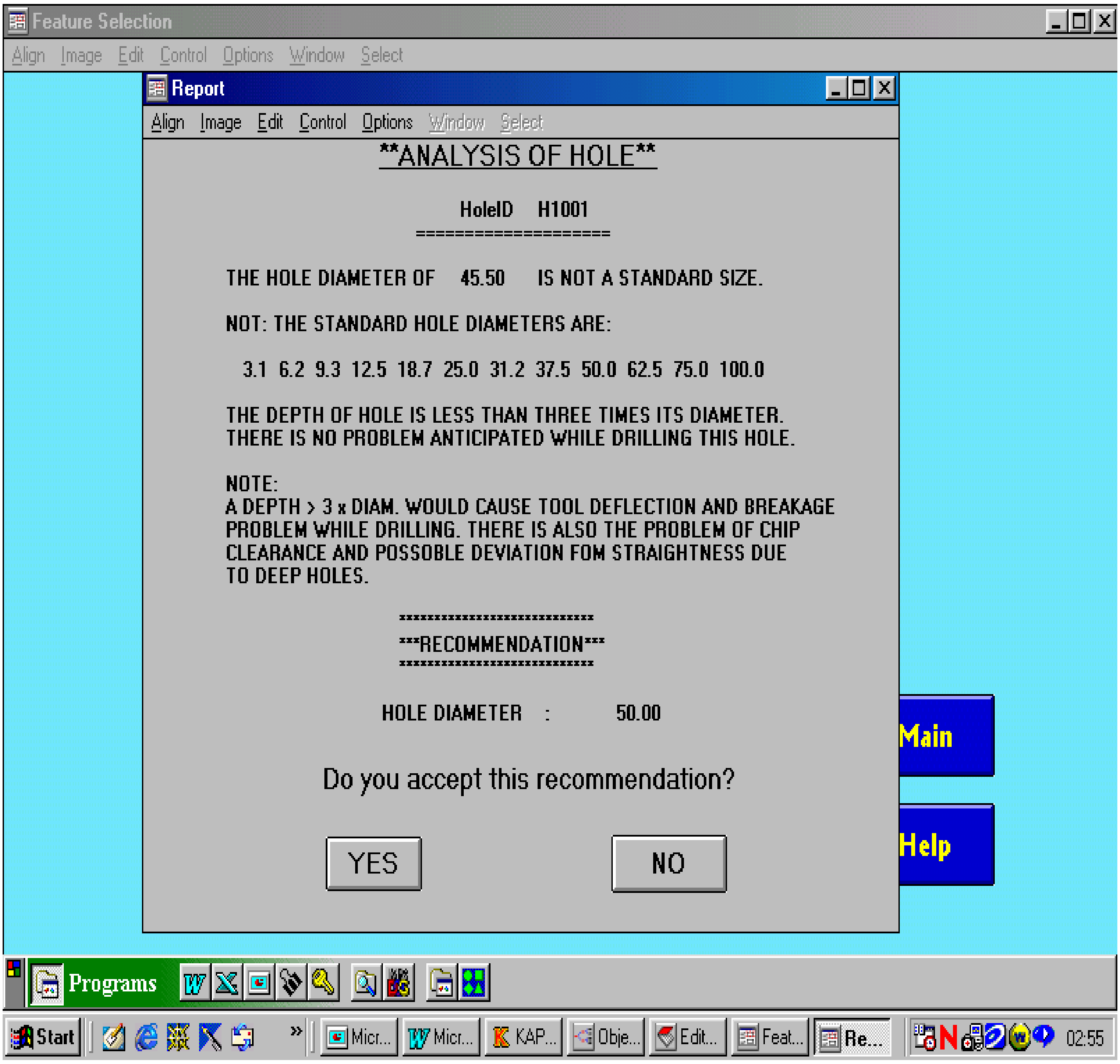


Figure (6.23) One System Recommendation for the Solid Model (Present Case Study)

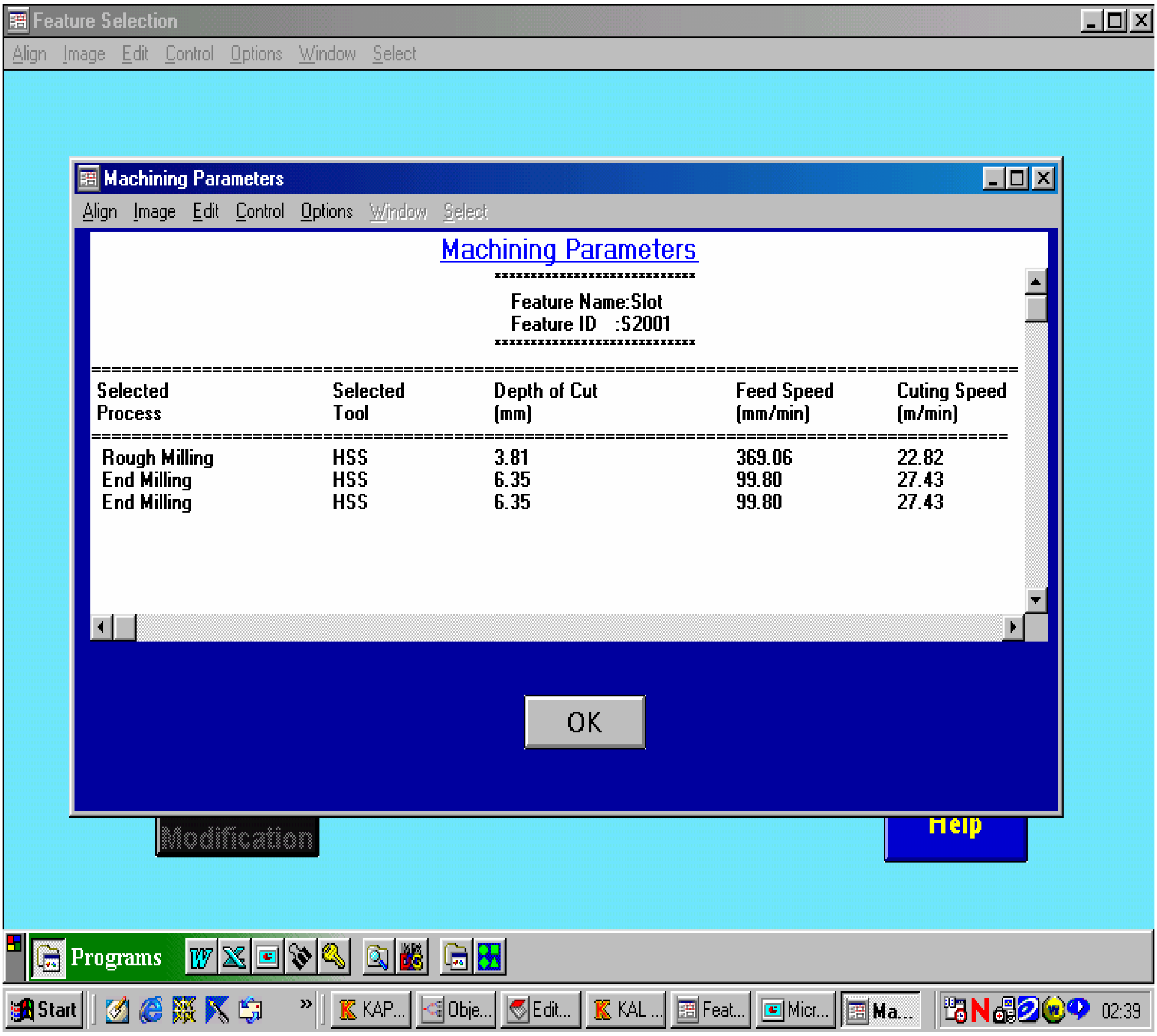


Figure (6.24) System Recommendation for Machining Parameters of Slot Making

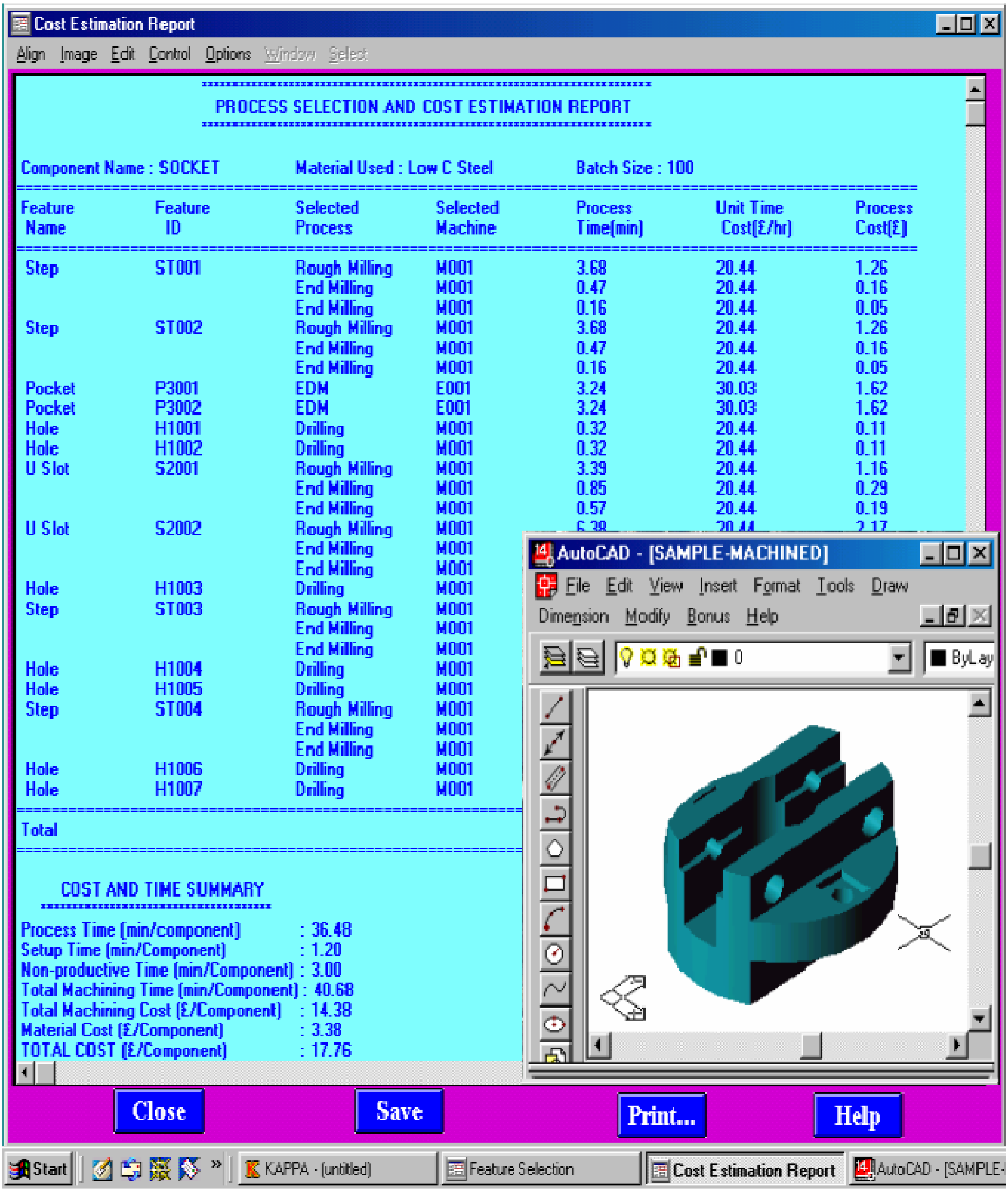


Figure (6.25) The System Window of the Cost Estimation Report of the Socket

6.5.3 Application of the Fuzzy Logic Model

The developed system has the capability to provide product cost estimation in the case of uncertainty of the product cost drivers. A machined component (socket) was used to demonstrate the implementation of the developed cost estimation fuzzy logic model. The developed model was presented in details in Section 4.4.2. As stated earlier, the cost drivers in the developed fuzzy logic model are the initial component volume, the component shape complexity, and the required surface finish of the component. While the output variable is the machining time.

In order to infer a conclusion, the truth-values of the various fuzzy notions defining the input variables should be determined. This depends on the user's knowledge regarding the cost drivers. One of the advantages of the fuzzy approach is that it is not necessary that the user precisely estimate the values for the cost drivers. Generally, there are two possibilities in the user's knowledge of an input variable, namely crisp value and linguistic expression. These two options are taken into consideration in the developed system as shown in Figure (6.26).

In the present case study, however the user is able to provide a relatively precise value of the initial component volume. He/she states a premise using a linguistic expression for the other two cost drivers. The shape complexity and the required surface finish of the component have been linguistically expressed as medium and polish, respectively. According to the production rules that are inserted into the system, the machining time is assigned as average.

Using the centroid defuzzification method, the linguistic expression of the machining time translates into a real value that represents the output value. The system estimates the machining cost (C_m) for producing the component based on the equation (4.6). The fuzzy logic cost estimation report indicates the input and output variables as shown in Figure (6.27).

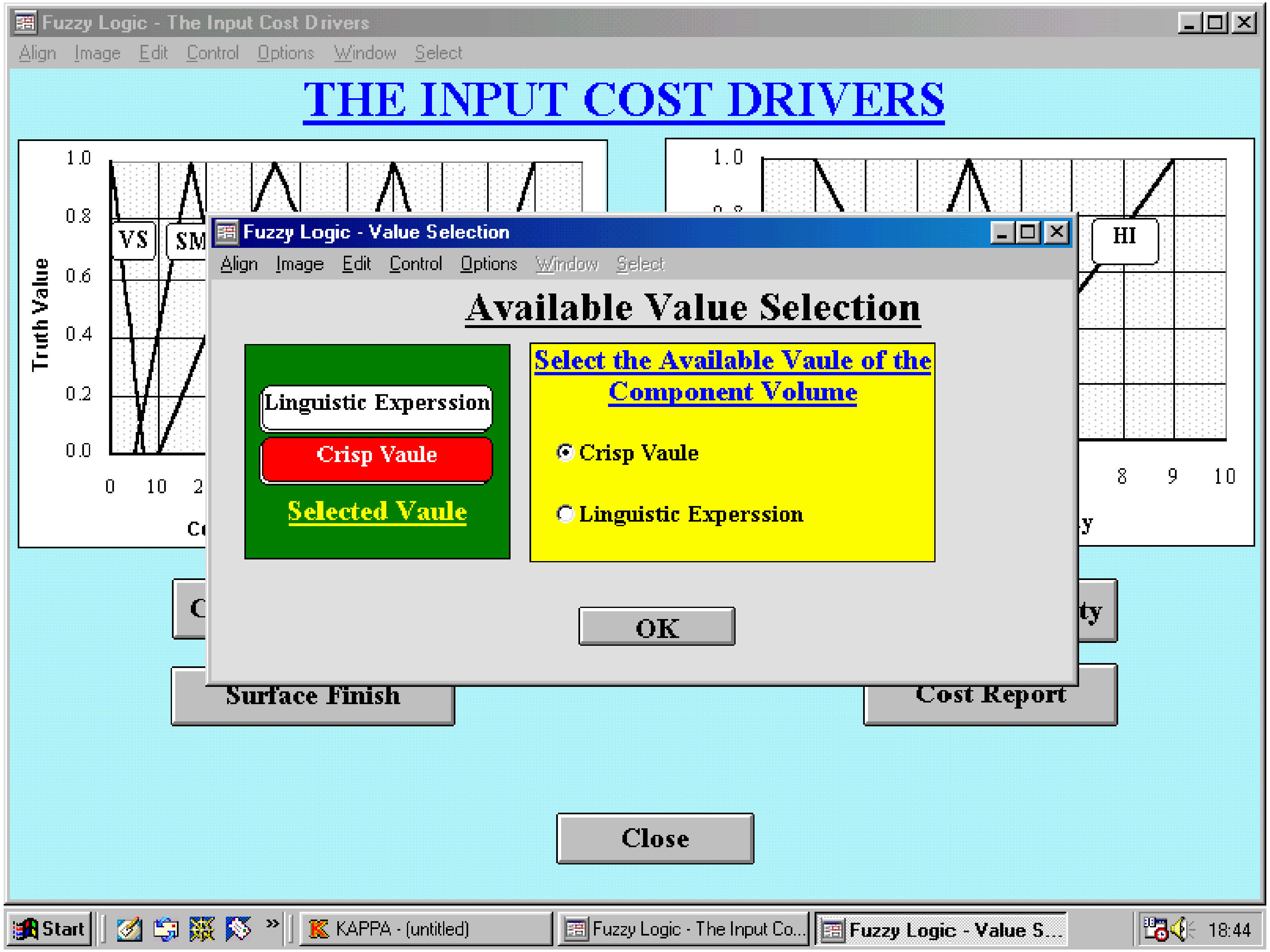


Figure (6.26) The Various Options to Input the Values of the Cost Drivers

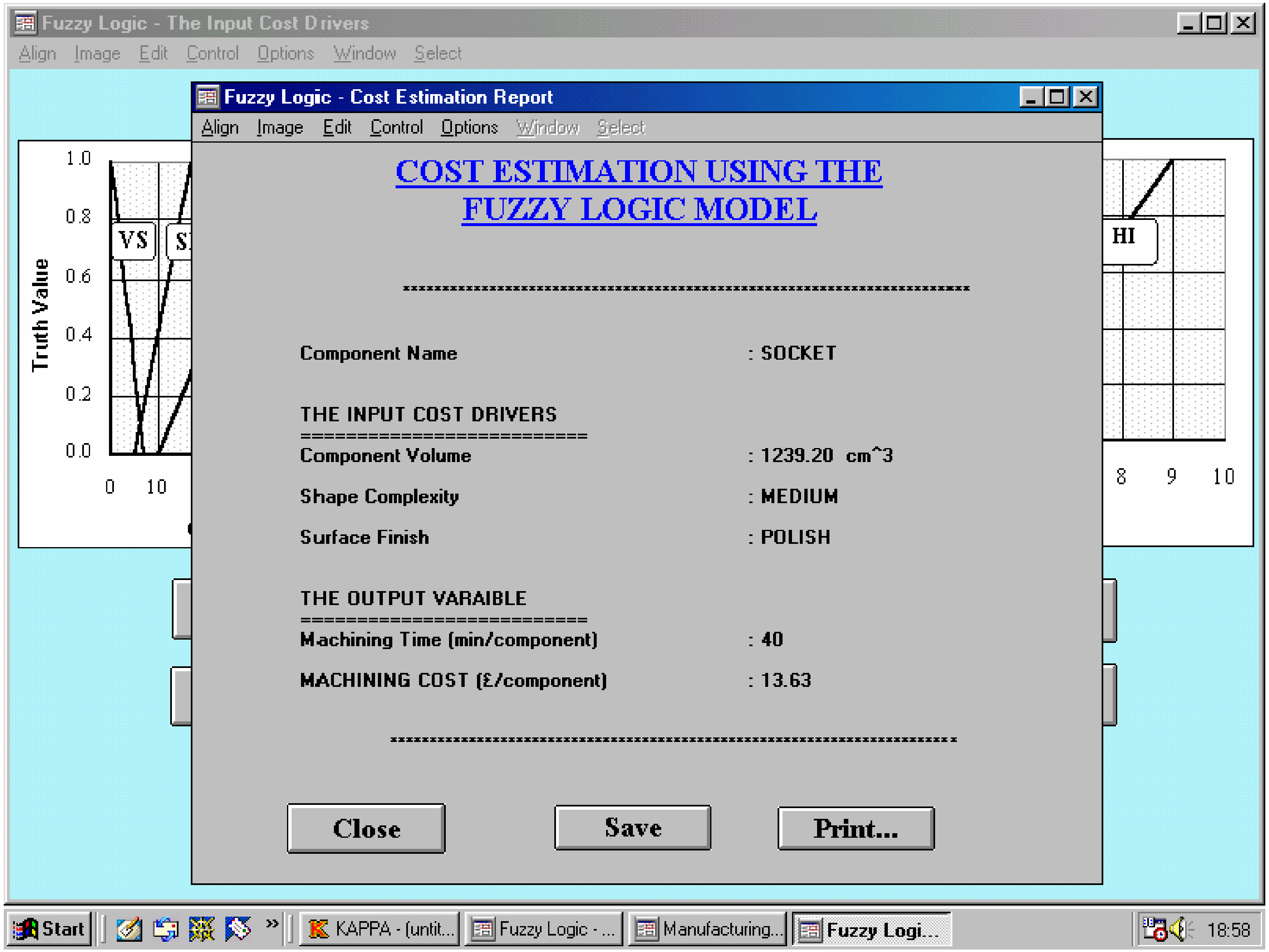


Figure (6.27) The Cost Estimation Fuzzy Logic Report Generated by the Developed System

6.6 Conclusion

The developed intelligent prototype system has been evaluated in this chapter through five products. The case studies showed that this system has potential for supporting the aims of CE and could be used by the designers efficiently to estimate a product's cost and analyse the design for assembly in the early stages of design. The conclusions taken from the case studies demonstrated that the objectives set out in Section 1.5 have been met by successful developing the system, which has the following major contributions to the area of CE:

- The developed system has been tested using an actual product, a scientific calculator. A 10% saving has been achieved by using the developed system.
- One of the unique advantages of the system is that it integrates the design evaluation, process selection, cost estimation, and design for assembly into a unified system. This feature is not available in any existing computer systems and packages.
- The system has been well designed to make it friendly to use.
- This system provides a designer with initial process plan.
- In the domain of DFA, the ability of the system to provide design improvement suggestions has been considered to be useful and practical.
- The manufacturing cost estimation, provided by the system, deviated from the actual manufacturing values by only a small margin. Therefore, the results suggest that the use of the system to generate early and accurate cost estimates for product designs is feasible.
- For cost modelling of manufacturing processes, the system has the capability to work with both machining processes and the injection moulding processes. The system has been integrated with CMS and a CAD system to retrieve the necessary material data and component attributes.

CHAPTER 7

7 OVERALL CONCLUIONS

7.1 Introduction

The cost of a product is a major factor in determining its commercial success. Therefore, it would be useful for the designer to have a product cost model to predict how design alternatives might affect costs of materials and fabrication. The research work described in this thesis has two major contributions to implementing the concurrent engineering philosophy namely, integration and optimisation. The research was carried out to integrate and optimise the various issues in a product life cycle, in a more consistent manner and in the early stages of the design process. This provides designers with knowledge about optimal product configurations, manufacturing and assembly costs.

The literature review in Chapter 2 indicated that current models could not offer a complete environment to the product cost modelling. This was because of limitations on the considerations of all aspects of the product life cycle. This necessitated complex and timely interactions between various areas. For this reasons, an intelligent knowledge-based system for product cost modelling and design for automation was developed in this research. The developed system enables designers to estimate the total product cost throughout the entire product life cycle. In addition, it provides designers with product design analysis for automation. It caters users with a rapid result via a user-friendly interface.

The system works in a fully interactive manner and guides users through several stages: selection the most economic assembly technique in order to consider this technique during the design process of the product, material selection capability by integration with CMS software, selection of machining processes and their machining parameters, estimating the total product cost ranging from material cost to assembly cost, design analysis for automation and providing the necessary redesign suggestions to simplify the assembly operations.

Based on the results attained from the developed system, the following are the major achievements of this research study:

1. An intelligent knowledge-based cost modelling environment for innovative product was successfully developed by incorporating various life cycle requirements into the cost-effective design process.

2. The system integration with Cambridge Materials Selector (CMS) and a CAD system, to facilitate the material selection process and retrieving the component parameters, were achieved.

3. A major achievement of this system is that it unified cost modelling, process sequence, machinability, and design for assembly into an integrated system.

4. The developed system has the potential to reduce the product cost by providing the designers with product cost effective design at the early stage of its elaboration.

5. The system enabled designers to carry out design feasibility for automation for their designs. In addition, it provided designers with the necessary suggestions for design improvement for automation assembly (Chapter 5).

6. In order to handle the uncertainty in cost estimation model that cannot be addressed by traditional analytical methods, a fuzzy logic model was developed and implemented successfully in the developed system to generate reliable estimation of costs.
7. Finally, the developed prototype system was tested via five case studies (Chapter 6). The results suggest that the use of the system to generate early and accurate cost estimates for product designs is feasible.

The major findings of this research work are summarised in the following sections.

7.2 Cost-effectiveness for manufacturing processes

Developing a prototype cost modelling system for innovative product development was the main concern in this study. The system was tested with several real machining and injection moulding components. The results drawn from the system were promising. Using this system, a significant reduction in the product cost and lead-time could be achieved. The developed cost modelling environment contained the following unique features:

1. It has the capability to generate initial process planning includes generation and selection of machining processes, their sequence and their machining parameters. The machining parameters comprise of cutting tool type and cutting conditions (e.g. feed rate and cutting speed).

2. The proposed system is applied without the need for detailed design information, so that it can be used at an early design stage and consequently redesign cost and longer lead-time can be avoided.

3. Efficient representation of cost, manufacturing, and design knowledge by the use of various knowledge representation approaches such as OOP, production rules, and frames to provide flexible, updateable and effective organisation of the knowledge necessary for cost analyses.

4. Generation feature-by-feature as well as the total product cost estimation report in order to highlight the features of high manufacturing cost. The cost estimation report can be saved as well as printed out for the user.

5. As the system is knowledge-based, this makes the system flexible and allows users to customise the knowledge stored in the knowledge bases in order to meet the requirements of individual companies.

6. A user-friendly interface, which consists of menus, active images and buttons, was achieved for providing the designers with easily input data to the system and complete results of the analysis.

7.3 Design analysis for assembly

A methodology for design for automation within a concurrent engineering of a product environment in order to give the designers the possibility to assess and reduce the total production cost of a product was developed.

The main contributions that are inferred from this novel methodology are cited as follows:

1. Hybrid knowledge representation techniques, such as production rules, frames and object oriented are employed to represent various types of assembly knowledge in this research.

2. Providing the designer with the facilitation for selecting the most economic assembly technique for the product based on the basic product specifications and the production data (production volume, number of components. etc.), at the early stages of the design process.

3. Estimating the assembly time and cost for manual, high-speed automatic, and robotic assembly systems.

4. Assembly automation and robotic assembly in specific are highly specialised fields, most designers do not have the necessary knowledge to meet all requirements to achieve a good design from the assembly point of view. Therefore, the system has the capability to analyse the product design for assembly automation.

5. Providing the designers with the necessary design improvement suggestions to simplify the assembly operations.

6. Providing designers with the complete and rapid results of the assembly technique selection, assembly time and cost estimation, design analysis for automation, and redesign suggestion via a user-friendly interface.

7.4 Summary

The developed system provided the designers with an interactive cost-effective design environment where successful concurrent product cost modelling and designs were achieved by:

- ***Full integration of the developed system with CMS and a CAD system,***

- ***Accurately forecasting the manufacturing time and cost of developing a new product. Consequently, quicker response to customers' expectations is generated,***

- ***User-friendly interface that would help the designer to use the system to its full potential,***

- ***Positive advice is generated that supports the designers in minimising the assembly cost and time by modification of the process and components design,***

- ***Selection of the optimum assembly system,***

- ***By using this system, the designer is giving the advantage of evaluating different concepts with manufacturing time and cost as decision-making criteria and can then help him to choose between different design alternatives,***

- ***The system can also be used as a design optimisation tool for the manufacturing time and cost of a new design or redesign.***

CHAPTER 8

8 RECOMMENDATIONS FOR FUTURE WORK

8.1 Overview

This research work has much contributed to the implementation of concurrent engineering strategy from three perspectives, integration, cost modelling and design for assembly. However, many interesting questions have been raised in this area of study. Further research is required to extend concurrent engineering framework so that the involvement of all issues related to the product's life cycle can be achieved, in order to satisfy all the requirements of the cost effective design for a product. A broader frame could be developed through suitable extensions of this research. Future research work that is necessary in this area of study is summarised in the following sections.

8.2 Cost Modelling of other Manufacturing Processes

The present work focused upon cost modelling of manufacturing processes including the assembly process. The cost estimation of other downstream process such as inspection, service, and disassembly is also a feasible research topic. These processes in turn, have a close relationship with the type of form features and their topological relationships and must be considered during the design stage.

Currently, the system was confined to modelling the costs of two manufacturing processes, namely machining and injection moulding processes. Further phases of the developed system should be carried out to model the costs of other manufacturing process, such as sheet metal, welding and casting processes, in order to make a enhance the cost modelling system. In the case of the injection-moulding module, the system should be extended to the process planning of mould-making, and providing injection moulding machine selection capabilities.

8.3 Process Selection and Optimisation

There are many issues related to process selection and optimisation that have to be exploited. These issues should be included in the cost modelling process in order to achieve the successful implementation of the concurrent product development. Further research effort is required in areas such as sequencing, tool path analyses and scheduling, in order to achieve the involvement of requirements of these areas in the cost modelling process.

8.4 Design for Assembly

The selection of an assembly system is usually based on cost-benefit analysis. Further research should be taken into the use of a neural network to estimate the cost of an assembly system as opposed to traditional regression or engineering analysis methods. Furthermore, a fuzzy logic-based model to deal with the uncertainty of assembly knowledge is a new topic that needs to be addressed.

Design analysis for robotic assembly does not sufficiently take into account the operations of checking, adjusting and other special processes needed. Further work concerning these processes should be carried out. Another aspect for future research is to build a knowledge-based model for selecting robotic systems for mechanical assembly. The knowledge-based model should have the capability to select a robot from available robotic systems based on cost and performance criteria along with the parameters for the assembly cell.

Automatic assembly sequence planning is recognised as an important tool for achieving concurrent product and process development thus reducing manufacturing costs. It plays an important role in designing and planning the assembly systems. Therefore, the present system should be extended, to generate and evaluate all feasible assembly sequences and assembly structure, automatically by determining and decomposing the levelled feasible subassemblies.

8.5 Integration

Concurrent engineering is a systematic approach. It aims to incorporate the product life cycle issues into the design phase. In this study, the integration of many of these issues has been achieved. However, there are other important areas that need to be involved in the design process, in order to bring the full benefits of the implementation of the concurrent engineering philosophy to manufacturers. For this reason, issues such as disassembly and recyclability must be integrated to achieve a higher level of concurrency between different design areas. Disassembly is the process of systematic removal of desirable constitute components from an assembly while ensuring that there is no impairment of the components due to the process. Further research in the area of disassembly should be carried out to encourage designers to design new products that are more environmental friendly and economic. The disassembly cost is a further research topic should be addressed. It can be categorised into three types, target disassembly, full disassembly, and optimal disassembly.

8.6 Expansion of the Knowledge-Based System

Work on expanding the system knowledge-based should continue in order to make the system more comprehensive. Research into the area of managing change in the knowledge-based couples with the latest advances in computer technology and advanced knowledge management tools would further improve the system.

REFERENCES

- **Abdalla HS** (1998) "A Concurrent Engineering Constraint-based System" *International Journal of Computers & Industrial Engineering*, Vol. 35, No. 3-4, pp. 459-462.

- **Abdalla HS** (1999) "Concurrent Engineering for Global Manufacturing" *International Journal of Production Economics*, 60-61, pp. 251-260.

- **Abdalla HS and Knight JAG** (1994a) “An expert system for concurrent product and process design of mechanical parts” *Proceedings of Instn Mech Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 208, No. 3, pp. 167-172.

- **Abdalla HS and Knight JAG** (1994b) **“**A Featured Based Design Environment for Concurrent Engineering" The Proceedings of the International Conference on CE and Electronic Design Automation- (CEEDA'94).

- **Aderoba A** (1997) “ A generalised cost-estimation model for job shops” *International Journal of Production Economics*, Vol. 53, No. 3, pp.257-263

- **Al-Ansary MD and Deiab IM** (1997) “Concurrent Optimisation of Design and Machining Tolerances using the Genetic Algorithms Method” *International Journal of Machine Tools Manufacturing*, Vol. 37, No. 12, pp. 1721-1731.

- **Al-Ashaab AHS and Young RIM** (1995) “Design for injection moulding in a manufacturing model environment” *Journal of Design and Manufacturing*, Vol. 5, pp. 45-54.

- **Alexander M, Srihari K and Emerson CR** (1994) “Cost based surface mount PCB design evaluation” *Journal of Electronic Testing: Theory and Applications*, Vol. 5, pp. 229-238

- **Allen AJ and Swift KG** (1990) " Manufacturing process selection and costing" *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 204, pp143-148

- **Allen AJ, Bielby MS and Swift KG (**1991) " Development of a product manufacturing analysis and costing system" *International Journal of Advanced Manufacturing Technology*, Vol. 6, pp. 205-215

- **Altrock C** (1996) "Practical fuzzy logic design" http://www.fuzzytech.com/e/e_a_pdf.html, (Accessed 11/02/2001)

- **Andreasen M, Kahler S and Lund T** (1983) "Design for assembly" IFS (Publications) Ltd., UK

- **Appleton E and Garside JA** (2000) "A team based design for assembly methodology" *Assembly Automation*, Vol. 20, No.2, pp. 162-169

- **Ashby MF** (1999) "Materials Selection in Mechanical Design" 2nd Edition, Oxford: Butterworth-Heinemann.

- **Asiedu Y and Gu P** (1998) " Product life cycle cost analysis: state of the art review" *International Journal of Production Research*, Vol. 36, No.4, pp.883-908

- **Baartman JP and Storm T** (1994) "Flexible Grippers for mechanical assembly" *International Journal of Industrial robot*, Vol. 21, No. 1, pp. 23-27

- **Barnes CJ, Dalgleish GF, Jared GEM, Swift KG and Tate SJ** (1997) "Assembly sequence structures in design for assembly" *Proceedings of the 1997 IEEE International Symposium on Assembly and Task Planning*, Marina Del Rey, CA., pp. 164-169.

- **Barnes CJ, Jared GEM and Swift KG** (1999) "Evaluation of assembly sequences in an assembly-oriented design environment" *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture* ,Vol. 231, pp. 89-93

- **Bedford A and Lo E** (1986) " Robots in assembly" Open University Press Robotics Series, England,

- **Bedworth DD, Henderson MR and Wolfe PM** (1991)" Computer Integrated Design and Manufacturing " McGraw-Hill Inc.

- **Beiter KA and Ishii K** (1996) "Incorporating dimensional requirements into material selection and design of injection moulded parts" *ASME Design Automation Conference,* Irvine, CA.

- **Bevan N, Jebb A and Wynn HP** (1989)" Design to cost" *Engineering design* Vol. 1 and 2, chi. 97, pp. 415-424

- **Boothroyd G** (1987) "Design for Assembly - the Key to Design for Manufacture" The *International Journal of Advanced Manufacturing Technology,* Vol.2, No. 3, pp. 3-11.

- **Boothroyd G** (1988) "Making it simple: Design for Assembly" *Mechanical Engineering,* February, pp. 28-31.

- **Boothroyd G** (1992) "Assembly automation and product design" *Marcel Dekker, Inc.*

- **Boothroyd G and Radovanovic P** (1989) " Estimating the cost of machined components during the conceptual design of a product" *Annals of CIRP,* Vol.38, no.1, pp. 157-160

- **Boothroyd G and Dewhurst P** (1983) "Design for Assembly Handbook" *Department of Mechanical Engineering, Massachusetts University, Amherst, MA 01003.*

- **Boothroyd G and Dewhurst P** (1987) "Product Design For Assembly" *Boothroyd Dewhurst Inc., 2 Holley road, Wakefield, RI, USA*

- **Boothroyd G and Reynolds C** (1989) " Approximate cost estimates for typical turned parts" *Journal of Manufacturing Systems* Vol.8, No.3, pp.185-193

- **Boothroyd G, Dewhurst P and Knight W** (1991)"Research program on the selection of materials and processes for component parts" *International Journal of Advanced Manufacturing Technology*, Vol. 6,pp. 98-111

- **Braggins D** (1995) "A critical look at robot vision" *International Journal of Industrial robot*, Vol. 22, No. 6, pp. 9-12

- **Bralla, J.G.** *Handbook of Product Design for Manufacturing*, 1986 (McGraw-Hill, New York).

- **Brinke ET, Lutters D, Streppel AH and Kals HJJ** (1999) "Variant cost estimation based on information management" *Proceedings of the 15th International Conference on Production Research (ICPR-15), Ireland*, Vol. 2, pp. 1383-1386. Also: http://www.opm.wb.utwente.nl/staff/erik/PHD/Publications.html, (Accessed 13.10.1999)

- **Britton G, Beng TS and Wang Y** (2000) "Virtual concurrent product development pf plastic injection moulds" *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 214, pp. 165-168.

- **Bruckner J and Ethrlenspiel K**. (1993) "Development of cost information tools for designer example-gear drives" *Proceeding of ASME Design for Manufacturability Conference*, pp.111-115

- **Bukkinger HJ and Richter M** (1991) "Integrated design and assembly planning" *Computer – Integrated Manufacturing Systems*, Vol. 4,No. 4, pp. 239-247

- **Buxton LL and Bull RJ** (1996) " An interactive cost estimating tool for the early stage of made -to-order product design" *Applications of Artificial intelligence in engineering* pp.111-

- **Cauchick-Miguel PA and Coppini NL** (1996) “Cost per piece determination in machining process: An alternative approach” *International Journal of Machine Tools Manufacturing,* Vol.36, No.8, pp. 939-946

- **Causey GC and Quinn RD** (1998) “Gripper design guidelines for modular manufacturing” *Proceedings of the IEEE internal conference on Robotics and Automation.*

- **Cay F. and Chassapis C** (1997)“ An IT view on perspectives of computer aided process planning research” *Computers in industry,* Vol.34, No.3, pp307-337

- **Champati S, Lu WF and Lin AC** (1996) “ Automated operation sequencing in intelligent process planning : A case-based reasoning approach” *International Journal of Advanced Manufacturing Technology*, Vol. 12, pp. 21-36

- **Chang HC, Dong L, Liu FX and Lu WF** (2000) “Indexing and retrieval in Machining process planning using case-based reasoning” *Artificial Intelligence in Engineering,* Vol.14, No. 1,pp. 1-13.

- **Chang KH, Silva J and Bryant I** (1999) “Concurrent Design and Manufacturing for Mechanical Systems” *Concurrent Engineering-Research and Applications* Vol. 7, No. 4, pp.1290-308.

- **Chang TC** (1990)” Expert process planning for manufacturing” Addison-Wesley.

- **Chang TC and Wysk RA** (1985) " An Introduction to Automated Process Planning Systems" Prentice Hall, Englewood, N.J.

- **Chang TC, Wysk RA and Wang HP** (1991) “Computer-Aided Manufacturing” Prentice Hall, Englewood, N.J.

- **Chen Y-M and Liu JI** (1999) " Cost-effective design for injection molding" *Robotics and Computer-Integrated Manufacturing,* Vol.15, No. 1, pp1-12

- **Chin KS and Pun KF** (1994) “Expert systems for concurrent engineering: an expert injection mould costing system” *Proceedings of International Conference of Data Knowledge Manufacturing Engineering*, Hong Kong, pp. 174-179.

- **Chin KS and Wong TN** (1995) “An expert system for injection mold cost estimation" *Advances in Polymer Technology*, Vol. 14, No. 4, pp 303-314.

- **Chin KS and Wong TN** (1996) “ Developing a knowledge-based injection mould cost estimation system by decision tables” *International Journal of Advanced Manufacturing Technology* ,Vol. 11, pp. 353-364

- **Chin KS and Wong TN** (1999) “Integrated product concepts development and evaluation” *International Journal of Computer Integrated Manufacturing*, Vol. 12, No. 2, pp 179-190.

- **Choi CK, Zha XF, Ng TL and Lau WS** (1998) “ On the automatic generation of product assembly sequences” *International Journal of Production Research*, Vol. 36, No. 3, pp.617-633

- **Cox E** (1994) "*The fuzzy systems handbook: A practitioner's guide to building, using, and maintaining fuzzy systems*" AP Professional. New York.

- **Creese RC and Li L** (1995) “Cost estimation in timber bridges using neural networks” *Cost Eng*, Vol. 37, No. 5, pp 17-22.

- **Crow K** (2001) “Customer-Focused Development with QFD” http://members.aol.com/drmassoc/QFD.html#anchor89284, (Accessed 28.06.2001).

- **Daabub A** (1999) “ An expert system for design for assembly” M.Phil. Thesis, De Montfort University, Leicester, England.

- **Daabub A and Abdalla H** (1999) "A computer-based intelligent system for design for assembly" *Computers & Industrial Engineering*, **37**(1-2), pp 111-115.

- **Das D, Gupta SK and Nau DS** (1994) “Reducing setup cost by automated generation of redesign suggestions” *Computers in Engineering, ASME,* Vol. 1,pp.159-170

- **D'cruz A** (1992) "Design for Assembly: Optimum Efficiency" *Manufacturing Breakthrough*, March/April, pp. 95-99.

- **Dean EB** (1995) “ Parametric Cost Deployment” *Proceedings of 7th Symposium on Quality Function Deployment*, Novi, MI, USA, 12-13 June, pp. 27-34. Also, http://mijuno.larc.nasa.gov/ebd/mypubs.html, (Accessed 01/03/2001)

- **Dean EB and Unal R** (1991) “Designing for Cost” *Transactions of the American Association of Cost Engineers, 35th Annual Meeting, 23-26 June*, Seattle WA, pp. D.4.1-D.4.6. Also, http://mijuno.larc.nasa.gov/ebd/mypubs.html, (Accessed 01/03/2001)

- **Dean EB and Unal R** (1992) “Elements of Designing for Cost” *AIAA, Aerospace Design Conference*, Irvine, CA, 3-6 February. Also, http://mijuno.larc.nasa.gov/ebd/mypubs.html, (Accessed 01/03/2001)

- **Devireddy CR and Ghosh K** (1999) “Feature-based modelling and networks-based CAPP for integrated manufacturing” *International Journal of Computer Integrated Manufacturing*, Vol. 12,No.1,pp. 61-74

- **Dewhurst P and Boothroyd G** (1988) “ Early cost estimating in product design” *Journal of Manufacturing Systems* vol.7, no.3, pp. 183-191

- **Diplaris SC and Sfantsikopoulos MM** (2000) "Cost-tolerance function. A new approach for cost optimum machining accuracy" *International Journal of Advanced Manufacturing Technology*, **16**(1), pp 32-38

- **Dong J and Parsaei HR** (1994)“ Design and implementation of a feature-based automated process planning (FBAPP) system” *Computers & Industrial Engineering* Vol.27, no.1-4 pp1-4

- **Downlatshahi S and Ashok MS** (1997) "Design Optimaisation in Concurrent Engineering: A Team Approach" *Concurrent Engineering-Research and Applications* Vol. 5, No. 5, pp.145-154.
- **DRM Associates** (2001) "The Principles of Integrated Product Development" http://members.aol.com/drmassoc/principles.html, (Accessed 28.06.2001).
- **Duverlie P and Castelain JM** (1999) "Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method" *International Journal of Advanced Manufacturing Technology*, Vol. 15, pp 865-906.
- **El Baradie MA** (1997) "A fuzzy logic model for machining data selection" *Int. J. Mach. Tools Manufact.,* Vol. 37, No. 9, pp 1353-1372.
- **El Baradie MA** (1998) "Industrial Applications of Fuzzy Logic" *Pacific Conference on Manufacturing*, Brisbine, Australia, pp. 143-148
- **Ersu E and Wienand S** (1995) "Vision system for robot guidance and quality measurement systems in automative industry" *International Journal of Industrial robot*, Vol. 22, No. 6, pp. 26-29
- **Fan I** (2000) "A Compact New Product Development Process and Information Model for SMEs" *6th International Conference on Concurrent Enterprising, 28-30 Jun 2000, Toulouse.*
- **Feng C, Kusiak A and Huang C** (1996) "Cost evaluation in design with form features" *Computer Aided Design*, vol.28, no.11, pp.875-885
- **Ferreirinha P, Hubka V and Eder WE** (1993) "Early cost calculation: Reliable calculation, Not just estimation" *Proceeding of ASME Design for Manufacturability Conference*, DE-Vol. 52, pp.97-104
- **French MJ** (1990) "Function costing: A Potential aid to designers" *journal of Engineering Design*, Vol. 1, No. 1, pp 47-53

- **French MJ and Widden MB** (1993) "Function-costing: A promising aid to early cost estimation" *Proceeding of ASME Design for Manufacturability Conference,* DE-Vol. 52, pp.85-90

- **Fung RYK and Popplewell K** (1994) "A neural network model for cost estimation and evaluation in manufacturing" *Advancement of Intelligent Production*, pp 69-74.

- **Gao JX and Huang XX**. (1996) " Product and manufacturing capability modelling in an integrated CAD/process planning environment" *International Journal of Advanced Manufacturing Technology* vol.11, pp 43-51

- **Gayretli A and Abdalla HS (**1999) **"**A prototype constraint-based system for automation and optimization of machining processes". *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture* , **213**, 655-676

- **Geiger TS and Dilts DM** (1996) " Automated design- to-cost- integrating costing into the design decision" *Computer-aided design* vol.28, no 6-7, PP423-438

- **GJ Edwards DW and Petley** (1993) "Chemical process plant cost estimating using fuzzy matching" *IEE, Savoy Place, London,* pp 4/1-4/3

- **Goodman CL, La-Brooy R and Travella L** (1991) "A user friendly package in design for assembly" *Transactions-of-the-Institution-of-Engineers, Australia, Mechanical-Engineering,* Vol. ME16, No.2, pp.117-22.

- **Grohmann U** (1996) "Paint robots in the automative industry – process and cost optimisation" *International Journal of Industrial robot*, Vol. 23, No. 5, pp. 11-16

- **Gun Ho Lee** (1997) " Reconfigurability consideration design of components and manufacturing systems" *International Journal of Advanced Manufacturing Technology* Vol.13, PP376-386

- **Gutowski T, Henderson R and Shipp C** (1991) "Manufacturing costs for advanced composite aerospace parts" *SAMP Journal*, Vol. 27, No. 3,pp.37-43

- **Hashmi K, El Baradie MA and Ryan M** (1999) “fuzzy-logic Based Intelligent Selection of Machining Parameters” *Journal of Materials Processing Technology,* Vol. 94, No. 2-3, pp. 94-111.

- **Hayes CC and Sun HC** (1995) “ Using a manufacturing constraint network to identify cost-critical areas of designs”, *AI EDAM- Artificial Intelligence for Engineering Design and Manufacturing* vol.9, No.2 pp73-87

- **Hegde GG** (1994) “Life cycle cost : A model and applications” *IIE Transactions,* Vol. 26,No. 6, pp. 56-62

- **Holland WV and Bronsvoort F** (2000) “Assembly features in modelling and planning” *Robotics and Computer-Integrated Manufacturing,* Vol.16, pp277-294

- **Hollingum J** (1999) “Flexible automation and robotics- a technology for all our tomorrows?” *International Journal of Industrial robot,* Vol. 26, No. 5, pp. 368-370

- **Hong TY and Tasi H** (1994) “ An integrated expert operation planning system with a feature- based design model” *International Journal of Advanced Manufacturing Technology* vol.9, pp305-310

- **Hundal MS** (1993a) “ Rules and models for low cost design”, *Proceeding of ASME Design for Manufacturability conference,* pp. 75-84.

- **Hundal MS** (1993b) “Design to cost” *Concurrent engineering Handbook,* (Ed. Parsaei, H.R. & Sullivan, W.G), Chapter 12, *Chapman & Hall*

- **Jahan-Shahi H, Shayan E and Masood S** (1999) "Cost estimation in flat plate processing using fuzzy logic" *Proceeding of the 24th Int. Conference on Computers and Industrial Engineering,* pp 485-488.

- **Jha NK** (1992) “Stochastic mathematical modelling and manufacturing cost estimation in uncertain industrial environment” *International Journal of Production Research,* Vol. 30, No. 12, pp. 2755-2771.

- **Jo HH, Parsaei HR and Sullivan WG** (1993) "Principles of Concurrent Engineering" *Concurrent engineering Handbook*, (Ed. Parsaei, H.R. & Sullivan, W.G), *Chapman & Hall*

- **Jovanoski D and Muthsam H** (1995) " Workpiece modelling for computer-aided process planning" *International Journal of Advanced Manufacturing Technology* vol.10, pp 404-410

- **Kanai S, Onozuka M and Takahashi H** (1995) "Optimal Tolerance Synthesis by Genetic Algorithm under the Machining and Assembling Constraints" *Proceedings of the 4th CIRP Seminar on Computer Aided Tolerancing*, Paris, France

- **Kanumury M and Chang TC** (1991) " Process planning in an automated manufacturing environment" *Journal of Manufacturing Systems* vol.10,no.1, pp67-78

- *Kappa-PC User's Guide*, 1993 (IntelliCorp, Inc, California).

- **Kazmer DO** (1997) "Best Practices in injection moulding" *Journal of Injection Moulding Technology*, Vol. 1, No.1, pp.10-17.

- **Kazmer DO and Speight RG** (1997) "Polymer injection moulding technology for the next millennium" *Journal of Injection Moulding Technology*, Vol. 1, No.2, pp.81-90.

- **Keys, L.K., Balmar, J.L., and Creswell, R.A.** (1987) "Electronic manufacturing process systems cost modelling and simulation tool" *IEEE Trans. Component Hybrids and manufacturing Technology*, Vol.CHMT-10, No.3, pp 401-410.

- **Kimmelmann, W. and Wolbring, F.** (2000) " First turnkey delivery of robotized assembly lines for car engines and cylinder heads" *International Journal of Industrial robot*, Vol. 27, No. 1, pp. 44-48

- **Kiritsis, D.** (1995) “A Review of knowledge-based expert systems for process planning. Methods and problems” *International Journal of Advanced Manufacturing Technology* , Vol. 10,pp. 240-262

- **Kouatli I and Jones B** (1990) “A guid to the design of fuzzy control systems for manufacturing process” *Journal of Intelligent Manufacturing*, Vol. 1, pp 231-244.

- **Koufteros X, Vonderembse M and Doll W** (2001) “Concurrent Engineering and its Consequences” *journal of Operations Management*, Vol. 19, No. 1, pp 97-115.

- **Kumar, S.; Shanker, K. & Lal, G.K.** (1999) "A feature recognition methodology for extrudable product shapes" *International Journal of Production Research*, Vol. 37, No. 11, pp. 2519-2544.

- **Kuo TC** (2000) "Disassembly Sequence and Cost Analysis for Electromechanical Products" *International Journal of Robotics and Computer Integrated Manufacturing*, Vol.16, pp. 43-54.

- **Kwong CK and Smith GF** (1998) “A computational system for process design of injection moulding: combining a blackboard-based expert system and a case-based reasoning approach” *International Journal of Advanced Manufacturing Technology* , Vol. 14,pp. 350-357.

- **Leikas, E.** (1999) “ Robot guidance with a photogrammetric 3-D measuring system” *International Journal of Industrial robot*, Vol. 26, No. 2, pp. 105-108

- **Lenau, T. & Haudrum, J.** (1994) “ Cost evaluation of alternative production methods” *Materials & Design*, Vol. 15, No. 4,pp 235-247

- **Lenz, J. & Neitzel, R.** (1995) “Cost modelling: An effective means to compare alternatives” *Industrial Engineering*, Vol.27, No.1, pp.18-19

- **Leung, A.C.K. ; Wainweight C.E.R. & Leonard, R.** (1996) “ The development of an integrated cost estimation system” *International Journal of Computer Integrated Manufacturing*, Vol. 9,No. 3,pp.190-204

- **Leung, H. C.** (1996) " Annotated bibliography on computer-aided process planning" *International Journal of Advanced Manufacturing Technology* vol. 12,pp. 309-329

- **Li, R-K & Hwang, C-L** (1992) "A framework for automatic DFA system development" *Computers Industrial Engineering*, Vol. 22, No. 4, pp.403-413.

- **London, P., Hankins, B., Spapossnek, M. and Luby, S.** (1987) " The cost and manufacturability expert: A customisable expert system" *Proceeding of the ASME International computers in Engineering Conference and Exhibition, ASME, New York*, pp. 125-129

- **Lucas Engineering & Systems Ltd** (1992) "Design For Assembly: Practitioners Manual" University of Hull, Version 8, LE& S/34.

- **Luong, L.H.S. and Spedding, T.** (1995) "An integrated system for process planning and cost estimation in hole making", *International Journal of Advanced Manufacturing Technology* vol.10, pp.411-415.

- **Lye, S-W & Ong N-S** (1993) "Computer assisted geometric analysis of components for automatic assembly" *Integrated Manufacturing Systems,* Vol.4, No. 2, pp. 4-14.

- ***Machine design***, 1997, vol.69, No.3, P100 " Software predicts manufacturing costs

- *Machinery's handbook***:** a reference book for the mechanical engineer, design. - 25th ed., 1996 (New York: Industrial Press).

- *Machining data handbook***,** 3rd edition, 1980, Vols. 1-2 (Mectcut Research Associations Inc.)

- **Mamalis, A.G., Malagardis, I. & Kambouris, K**. (1996) " On-line integration of a process module with production scheduling" *International Journal of Advanced Manufacturing Technology* vol.12, pp. 330-338

- **Marri, H. B.; Gunasekaran, A. & Grieve, R.J.** (1998) "Computer-aided process planning: A state of art" *International Journal of Advanced Manufacturing Technology*, Vol. 14,pp. 261-268

- **Mason AK and Levy A** (1996) "Fuzzy expert systems for parametric cost estimating" *Proc. 7th Ann. Conf. Int. Soc. Parametric Analysis, pp METH.15-METH.32*

- **Mason, A.K. & Kahn, D.J.** (1997) "Estimating costs with fuzzy logic" *AACE International Transactions,* EST.03.1-EST.03.6

- **McIlhenny, R.C., Sethumadhave, T.S.; Lee, K.S. and Keys, L.K**. (1993)" An integrated system approach to facilitate early cost estimation", *Proceeding of ASME Design for Manufacturability Conference, pp.105*-109

- **McKim RA** (1993) "Neural network applications to cost estimation" *Cost Eng*, Vol. 35, No. 7, pp 31-35.

- **Mileham, A.R., Currie, G.C., Miles, A.W. & Bradford, D.T.** (1993) "A parametric approach to cost estimating at the conceptual stage of design" *Journal of Engineering Design,* Vol. 4, No. 2, pp. 117-125

- **Mirakon, P.F., Eth-Uno, V.H. And Eder, W.E**. (1993) "Early cost calculation: reliable calculation, not just estimation", *Proceeding of ASME Design for Manufacturability conference*, pp.97-104

- **Miyakawa, S.; Ohashi, T. & Iwata, M.** (1990) "The Hitachi new assembly evaluation method (AEM*)" Transaction of NAMRI/SME*, PP.352-359

- **Mok, C.K.; Chin, K.S. and Ho, K.L.** (2001) "An interactive knowledge-based CAD system for mould design in injection moulding processes" *International Journal of Advanced Manufacturing Technology*, Vol.17, pp 27-38

- **Molloy, E., Yang, H. & Browne, J.** (1993) “Feature-based modelling on design for assembly” *International Journal of Computer Integrated Manufacturing, Vol*. 6,No. 1,PP.119-125

- **Monfared, R.P.; Hodgson, A.; Bowen, B.A. & West, A.A.** (1998) “Implementing a model-based generic user interface for computer integrated manufacturing systems” *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture* ,Vol. 212, No. 7,pp. 501-516

- **Moor, L.T. & Creese, R. C.** (1990) “ Manufacturing cost estimation” *Cost Engineering,* vol.32, No.5, pp 17-21

- **Nevins JL, Whitney DL** (1989) "*Concurrent design of products and processes"* McGraw Hill Inc, New York.

- **O’Shea, B.; Kaebernick, H.; Grewal, S.; Muller, K. and Seliger, G.** (1999) “Method for automatic tool selection for disassembly planning” *Assembly Automation,* Vol. 19, No.1, pp. 47-54

- **Offodile, O. F.; Marcy, W.M. and Johnson, S.L.** (1991) “ Knowledge base design for flexible assembly robots” *International Journal of Production Research,* Vol.29, No. 2, pp. 317-328

- **Ong, N.S.** (1995) “ Manufacturing cost estimation for PCB assembly: An activity-based approach” *International Journal of Production Economics,* Vol. 38, pp. 159-172

- **Ostwald PF.** (1988) "AM Cost estimator" 4th Ed, McGraw Hill Inc, New York.

- **Ostwald, P.F.** (1992) “Engineering cost estimating” 3rd.ed,Englewood Cliffs: Prentice Hall.

- **Ouyang, C & Lin, TS** (1997) “ Developing an integrated framework for feature-based manufacturing cost estimation” *International Journal of Advanced Manufacturing Technology,* Vol. 13,No. 9, pp.618-629

- **Owen T.** (1985) " Assembly with robots" *Tony Owen.*

- **Parsaei, H.R. & Sullivan, W.G.** (1993) "Concurrent engineering Handbook", *Chapman & Hall*

- **Parsons, C.W.S.** (1957) "Estimating machining costs" *McGraw – Hill*

- **Patterson, B. & Cirstea, M.** (1995) " Concurrent engineering - a modern approach to a system design" *Advances in Design and Manufacturing*, Vol. 6, pp. 179-188

- **Petley GJ and Edwards DW** (1995) " Further Developments in chemical plant cost estimating using fuzzy matching" *Computers Chem. Eng*., Vol. 19, pp S675-S680

- **Pham DT and Dimov SS** (1998) "An approach to Concurrent Engineering" *Proceedings of Instn Mech Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 212, pp 13-27.

- **Pham DT and Ji C** (1999) "A concurrent design system for machined parts" *Proceedings of Instn Mech Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 213, pp 841-847.

- **Pham, D.T. and Yeo, S.H.** (1991) "Strategies for gripper design and selection in robotic assembly" *International Journal of Production Research*, Vol.29, No. 2, pp. 303-316

- **Pham, DT & Pham, PTN** (1998) " Expert systems in mechanical and Manufacturing engineering" *International Journal of Advanced Manufacturing Technology*, Vol. 3, no. 3, pp 3-21.

- **Ping, L., Yongtong, H., Bode, J. and Shouju, R.** (1996) " Multi-agent system for cost estimation" *computers ind Engng*, Vol.31, No. ¾, pppp. 731-735

- **Rampersad, H.K.** (1994) "Integrated and simultaneous design for robotic assembly" *John Wiley & Sons Ltd.*

- **Rampersad, H.K.** (1995a) " State of the art in robotic assembly" *International Journal of Industrial robot,* Vol. 22, No. 2, pp. 10-13
- **Rampersad, H.K.** (1995b) "Concurrent design of product, process and robotic assembly system" *Assembly Automation,* Vol. 15, No. 1, PP.21-28.
- **Ranky, P.G.** (1999) "Design, manufacturing and assembly automation trends and strategies in China" *Assembly Automation,* Vol. 19, No.4, pp. 301-305
- **Ray, L.P.** (1996) "Robot disassembles explosive devices" *International Journal of Industrial robot,* Vol. 23, No. 3, pp. 20-24
- **Rehman, S. & Guenov M.D.** (1998) "A Methodology for modelling manufacturing costs at conceptual design" *Computers and Industrial Engineering,* Vol 35, No. 3-4, pp. 623-626
- **Rehman, S. &A.J. Morris** (1996)" A Knowledge-based approach to modelling manufacturing costs at the design phase of a product's life-cycle", *Proceedings of the conference on integration in manufacturing, Galway, Ireland.*
- **Rehman, S.** (1997) " A Methodology for modelling manufacturing costs at conceptual design," *Proceedings of 22nd international conference on computers and industrial engineering AUC, Cairo.*
- **Rosato DV, Rosato PE** *Injection moulding handbook.* 2nd edition, 1996 (Van Nostrand Reinhold Company, New York).
- **Rosenfield, D.B.** (1996) "Global and variable cost manufacturing systems" *European Journal of Operational Research,* Vol. 95,No.2, pp.325-343
- **Salomons OW, van Houten FJAM and Kals KJJ** (1993) "Review of Research in Feature-Based Design" *Journal of Manufacturing Systems,* Vol. 12, No. 2, pp. 113-131.

- **Salomons, O.W; Van Houten, F.J.A.M & Kals, H.J.J**. (1993) " Review of Research in Feature-based Design" *Journal of Manufacturing Systems*, Vol.12, No.2, pp. 113-132

- **Schreve, K.; Schuster, H.R. and Basson, A.H.** (1999) "Manufacturing Cost Estimation During Design of Fabricated Parts" *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture*, Vol. 231, pp. 231-243

- **Senechal, O. & Tahon, C**. (1997) " A Modelling approach for production costing and continuous improvement of manufacturing processes" *Production Planning & Control*, Vol. 8, no.8, pp.731-742

- **Senin N, Groppetti R and Wallace D** (2000) "concurrent assembly Planning with Genetic Algorithms" *International Journal of Robotics and Computer Integrated Manufacturing*, Vol.16, pp. 65-72.

- **Shehab, E. M. and Abdalla, H. S.,** (2001a) "An Intelligent Knowledge based system for Product Cost Modelling" *International Journal of Advanced Manufacturing Technology*, (Expected to be published in volume 18).

- **Shehab, E. M. and Abdalla, H. S.,** (2001b) "Manufacturing cost modelling for concurrent product development" *International Journal of Robotics and Computer Integrated Manufacturing*, Vol. 17, No. 4, pp 341-353.

- **Shehab, E. M. and Abdalla, H. S.,** (2001c) "A design to cost system for innovative product development" *Proceedings of Inst. Mech. Engrs (IMechE), Part B: Journal of Engineering Manufacture*, (Submitted).

- **Shehab, E. M. and Abdalla, H. S.,** (2001d) "An integrated prototype system for cost effective design" *Concurrent Engineering: Research and Application (Special Issue in Cost Modelling)*, (Expected to be published in December 2001).

- **Sheldon, D.; Huang, G. and Perks, R**. (1991)"Design for cost: Past experience and recent development" *journal of Engineering Design*, Vol. 2, No. 2, pp127-139
- **Sheldon, D.; Huang, G. and Perks, R**. (1993) "Specification and development of cost estimating databases for engineering design" *Proceeding of ASME Design for Manufacturability Conference*, pp.91-96.
- **Sheldon, D.F., Perks, R., Jackson, M., Miles, B.L. & Holland, J.** (1990) "Design for whole life costs at the concept stage" *Journal of Engineering Design*, Vol. 1, No. 1, pp. 131-145
- **Shing, O.N.** (1999) "Design for manufacture of a cost-based system for molded parts" *Advances in Polymer Technology*, **18**(1), pp.33-42
- **Sivaloganathan, S ; Jebb, A & Evbuomwan, NFO** (1994)" Design for cost within the taxonomy of design function deployment", *Proceedings of 2nd international conference on concurrent Engineering and electronic design automation*, Ch.83, pp. 14-19
- **Smith AE and Mason AK** (1997) "Cost estimation predictive modeling: Regression versus Neural Network" *The Engineering Economist*, Vol. 42, No. 2, pp 137-161.
- **Smith R, Barton R, Nowack C, Zayas-Castro J** (2001) "Concurrent Engineering: A Partnership Approach" http://www.me.psu.edu/lamancusa/html/ConcEng.htm (Accessed 26.06.2001)
- **Smith, A.E. & Mason, A.K.** (1997) "Cost estimation predictive modelling: Regression versus neural network" *The Engineering Economist*, Vol.42,No.2, pp. 137-161
- **Stewart RD, Wyskida RM and Johannes JD** (1995) "Cost Estimator's Refernce Manual" *John Wiley & Sons.*
- **Stewart, R.D**. *Cost Estimating*, 2nd Ed, 1991 (John Wiley & sons).

- **Strobl, G. and Dodenhoft, D.** (1992) “DFA-XPRT: A knowledge-based approach for design analysis in mechanical engineering” *Computers and Artifical Intelligence,* Vol. 11, No. 5, pp. 425-456

- **Tatikonda, L.U. & Tatikonda, M.V.** (1994) “Tools for cost-effective product design and development” *Production and Inventory Management Journal,* Vol.35, No.2, pp. 22-28

- *The Cambridge Materials Selector (CMS),* Version2.0, 1994 (Granta Design Ltd).

- **Tseng, Y.J. and Jiang, B.C.** (2000) “ Evaluating Multiple feature-based machining methods using an activity-based cost analysis model” *International Journal of Advanced Manufacturing Technology*, Vol.16, pp 617-623

- **Ufford, D.A.** (1996) “Leveraging commonalties between DFE and DFM/A” *IEEE.*

- **Venkatachalam, A.R.** (1993) “Automating Design for Manufacturability Through Expert systems Approaches” *Concurrent engineering Handbook*, (Ed. Parsaei, H.R. & Sullivan, W.G), Chapter 23, *Chapman & Hall*

- **Venkatachalam, A.R.** (1994) "Automating manufacturability evaluation in CAD systems through expert systems approaches" *International Journal of Expert Systems with Application,* Vol. 7, No. 4, pp 495-506

- **Venkatachalam, A.R. ; Mellichamp, J.M. & Miller, D.M.** (1993) “A knowledge-based approach to design for manufacturability” *Journal of Intelligent Manufacturing,* Vol. 4, pp. 355-366

- **Wang Q, Stockton DJ and Baguley P** (2000) “Process cost modelling using neural networks” *International Journal of Production Research,* Vol. 38, No. 16, pp. 3811-3821.

- **Waterbury, R.** (1986) "Applying Design for Assembly Principles" *Assembly engineering,* Vol. 3, pp. 42-45.

- **Wei, C.C.; Liu, P.H. and Chen, C.B.** (2000) "An automated system for product specification and design" *Assembly Automation*, Vol. 20, No.3, pp. 225-232

- **Wei, Y. & Egbelu, P.** (2000) " A framework for estimating manufacturing cost from geometric design data" " *International Journal of Computer Integrated Manufacturing*, Vol. 13,No.1, pp. 50-63

- **Wierda L. S.** (1991) " Linking design, process planning and cost information by feature-based design modelling" *Journal of Engineering Design*, Vol. 2, No. 1, pp. 3-19

- **Wierda, L.S.** (1990) "Design-oriented cost information: the need and the possibilities" *Journal of Engineering Design*, Vol. 1, No. 2, pp. 147-167

- **Wilhelm M, Smith A and Bidanda B** (1995) " Integrating an expert system and a neural network for process planning" *Engineering Design and Automation*, Vol. 1, No. 4, pp 259-269.

- **Wilson, M.** (1999) "Vision systems in the automotive industry" *International Journal of Industrial robot*, Vol. 26, No. 5, pp. 354-357

- **Wong SV, Hamouda AMS and El Baradie MA** (1999) "Generalized Fuzzy Model for Metal Cutting Data Selection" *Journal of Materials Processing Technology*, Vol. 89-90, pp. 310-317.

- **Wu RR and Zhang YY** (1998) "A CAPP Framework and its Methodology" *International Journal of Advanced Manufacturing Technology*,Vol. 14, pp 255-260

- **Wu, T. and O'Grady, P.** (1999) "A concurrent engineering approach to design for assembly" *Concurrent Engineering-Research and Applications* Vol. 7, No. 3, pp.231-243

- **Wysk RA, Peters BA and Smith JA** (2001) "A Formal Process Planning Schema for Shop Floor Control" http://tamcam.tamu.edu/pubs/ppfinal.htm, (Accessed 26.02.2001)

- **Ye, X.G.; Fuh, J.Y.H. and Lee, K.S.** (2000) "Automated assembly modelling for plastic injection moulds" *International Journal of Advanced Manufacturing Technology*,Vol.16, pp 739-747

- **Yeo, S.H., Ngoi, B.K.A. , Poh, L.S. and Hang, C.** (1997) "A cost-tolerance relationships for non-traditional machining processes" *International Journal of Advanced Manufacturing Technology*,Vol.13, pp 35-41

- **Yeo, S.H., Ngoi, B.K.A. and Chen, H.** (1996) "A cost-tolerance model for process sequence optimisation" *International Journal of Advanced Manufacturing Technology*,Vol.12, pp 423-431

- **Yoshimura M. and Takeuchi A.** (1994)" Concurrent optimisation of product design and manufacturing based on information of users needs" *Concurrent Engineering-Research and Applications* Vol. 2, No. 1, pp.33-44

- **Zadeh LA** (1965) "Fuzzy sets" *Information and Control*, Vol. 8, pp 338-353

- **Zha X. F., Lim S.Y.E. and Fok S.C.** (1999a) "Integrated knowledge-based approach and system for product design for assembly" *International Journal of Computer Integrated Manufacturing*, Vol. 12, No.3, pp 211-237

- **Zha X.F., Lim S.Y.E. and Fok S.C.** (1999b) "Development of expert system for concurrent product design and planning for assembly" *International Journal of Advanced Manufacturing Technology*, Vol.15 , pp 153-162

- **Zhang Y.F., Fuh J.Y.H. and Chan W.T.** (1996) "Feature-based cost estimation for packaging products using neural networks" *Computers in Industry*, Vol. 32,No.1, pp.95-113.

APPENDIX (PUBLISHED PAPERS)