Proceedings of the Institution of Mechanical Engineers. Part B.
Journal of engineering manufacture, 2002, vol. 216, no7, pp. 999-1019

A design to cost system for innovative product development

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Abstract: This research paper presents a prototype object-oriented and rule-based system for product cost modelling and design for automation at an early design stage. The developed system comprises a computer aided design (CAD) solid modelling system, a material selection module, a knowledge-based system (KBS), a process optimization module, a design for assembly module, a cost estimation module and a user interface. The system development process has passed through four major steps: constructing the knowledge-based and process optimization system; developing a design for assembly module; integrating the KBS with both a material selection database and the CAD system; developing and implementing a fuzzy logic approach to generate reliable estimation of cost and to handle the uncertainty in the cost estimation model that cannot be addressed by traditional analytical methods. Two manufacturing processes, namely machining and injection moulding processes, were considered in the developed system.

The main function of the system, besides estimating the product cost, is to generate initial process planning, including the generation and selection of machining processes, their sequence and their machining parameters, and to recommend the most economical assembly technique for a product and provide design improvement suggestions based on a design feasibility technique. In addition, a feature-by-feature cost estimation report is generated using the proposed system to highlight the features of high manufacturing cost. Two case studies were used to validate the developed system.

Keywords: concurrent engineering, manufacturing cost modelling, process optimization, object-oriented programming, feature-based CAD, fuzzy logic

1 INTRODUCTION

The product development process encompasses several issues, including marketing, conceptual design, detail design, process selection and cost estimation. Concurrent engineering (CE) increases industrial competitiveness by shortening product development time, improving quality and decreasing costs. One of the targets of CE philosophy is to utilize all information about the product life cycle simultaneously and as early as possible to avoid or minimize expensive iterations. Therefore, estimating manufacturing cost at an early design stage is a vital task.

It has been reported that up to 70 per cent of the total product cost is committed at the early stage of the design process [1]. However, the design phase itself accounts for only 6 per cent of the total development cost [2, 3]. Therefore, decision-making at the design stage has a greater impact than at the manufacturing stage. Also, it is necessary to provide the designer with an efficient cost modelling tool. Cost estimation is concerned with the prediction of costs related to a set of activities before thay have actually been executed. Cost modelling approaches, at the design stage, can be broadly classified as knowledge based [4], feature based [5, 6], function based [7] and operations based [8].

Shehab and Abdalla [2] developed an intelligent knowledge-based system for product cost modelling at an early design stage. The earlier version of the developed system has taken into consideration processing and material costs. The current further development addressed other essential issues such as non-productive cost and set-up cost. In addition, a design for automation module has been considered in the developed prototype system.

Diplaris and Sfantsikopoulos [9] presented a new analytical cost tolerance model that correlates almost all the main items relating to the derivation of the cost of the machining accuracy. A framework to estimate

The MS was received on 11 January 2002 and was accepted after revision for publication on 21 March 2002.
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the lowest product manufacturing cost from its AND/OR tree representation of an alternate process was developed by Wei and Egbelu [**10**]. The framework focused only on processing and material handling costs without considering other direct product costs such as set-up, material, fixtures and labour cost. Research work in manufacturing process selection, optimization, product and process design can be found in references [**11**] to [**13**].

A few models were developed to estimate the cost for producing specific categories of products. For instance, research to obtain the cost information for gear drives was carried out by Bruckner and Ehrlenspiel [**14**]. An expert system for process selection and cost estimation for cast and forged products was developed by Venkatachalam *et al.* [**15**]. The role of cost models in design for manufacturing and the requirements for a design for manufacturing cost estimation are reported by Schreve *et al.* [**16**].

Recent research work has been carried out in the area of developing cost models for injection-moulded components [**17–19**]. Assembly cost estimation was one of the criteria used to determine the most economical assembly technique for a product [**20**].

Fuzzy logic has been used as the basis for controlling industrial processes and consumer products. El-Baradie [**21**] developed a fuzzy logic model for machining data selection. A fuzzy logic expert system for estimating excavation cost was developed by Mason and Kahn [**22**].

The literature review indicated that little effort was made in cost modelling at an early stage of the entire product development cycle. Other limitations of the existing systems are that most of them deal with cost estimation of existing products rather than new products. They also lacked the material selection capability. It is also apparent that all aspects of the product life cycle such as the assembly stage were not considered in these systems.

To overcome the above shortcomings, an integrated working prototype system for product cost modelling has been developed in this project. The developed system has taken into consideration all the aspects of the entire product development process.

2 OVERALL STRUCTURE OF THE DEVELOPED SYSTEM

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

The developed system for cost modelling comprises a computer aided design (CAD) solid modelling system, a material selection module, a knowledge-based system (KBS), a process optimization module, a design for assembly module, a cost estimation module and a user interface. In addition, the system encompasses two types of database, permanent (static) and temporary (dynamic). These databases are categorized into five separate groups of database:

(a) feature database,
(b) material database,
(c) machinability database,
(d) machine database,
(e) mould database.

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 Fig. 1. In addition to design for assembly, two manufacturing processes were considered in the proposed system. These processes are the machining processes and the injection moulding process. In this paper, cost modelling of a machined component will be considered. More details of the developed system can be obtained from reference [**23**]. The various components of the developed system will be discussed in the following sections.

2.1 Material selection/costing module

Material selection is an important stage and a complicated one that is made early in the design process. The direct material cost frequently forms more than 50 per cent of the total product cost [**20**] and therefore should be estimated with reasonable care. 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 (see Fig. 2). The first option is that the user selects to specify the material based on his own criteria. The second one is that the system executes Cambridge Material Selection (CMS) software [**24**]. 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. With CMS, the most appropriate material will be determined on the basis of previous input of product concepts and requirements.

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 will be used to store the data about the selected material such as the specification and unit cost of the material. The material cost, C_{mt}, can be

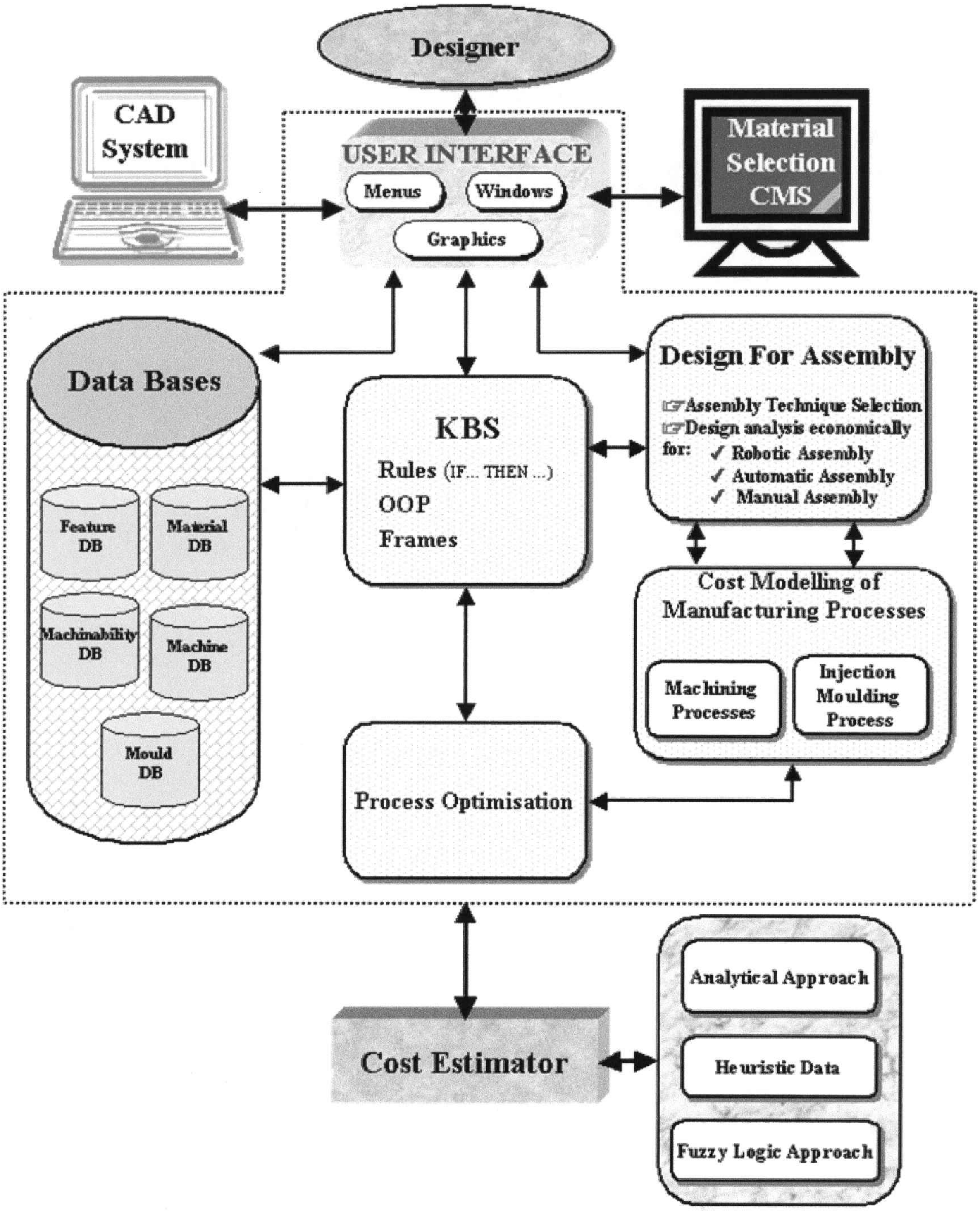


Fig. 1 Overall structure of the developed system

estimated using the following equation:

$$C_{\mathrm{mt}} = V\rho C_{\mathrm{w}} \tag{1}$$

where

V = raw material component volume (m^3)
ρ = material density ($\mathrm{kg/m}^3$)
C_{w} = unit price (£/kg)

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

2.2 Knowledge bases

Knowledge representation is the formal description of the knowledge with symbolic encoding. It deals with how to organize and encode knowledge in the best form so that problems can easily be solved. Many representation techniques, such as production rules, object orientation and semantic network and framework, have been reported in AI, to meet the requirements for specific problems. The knowledge-based systems (KBSs) were written in a modular structure, namely

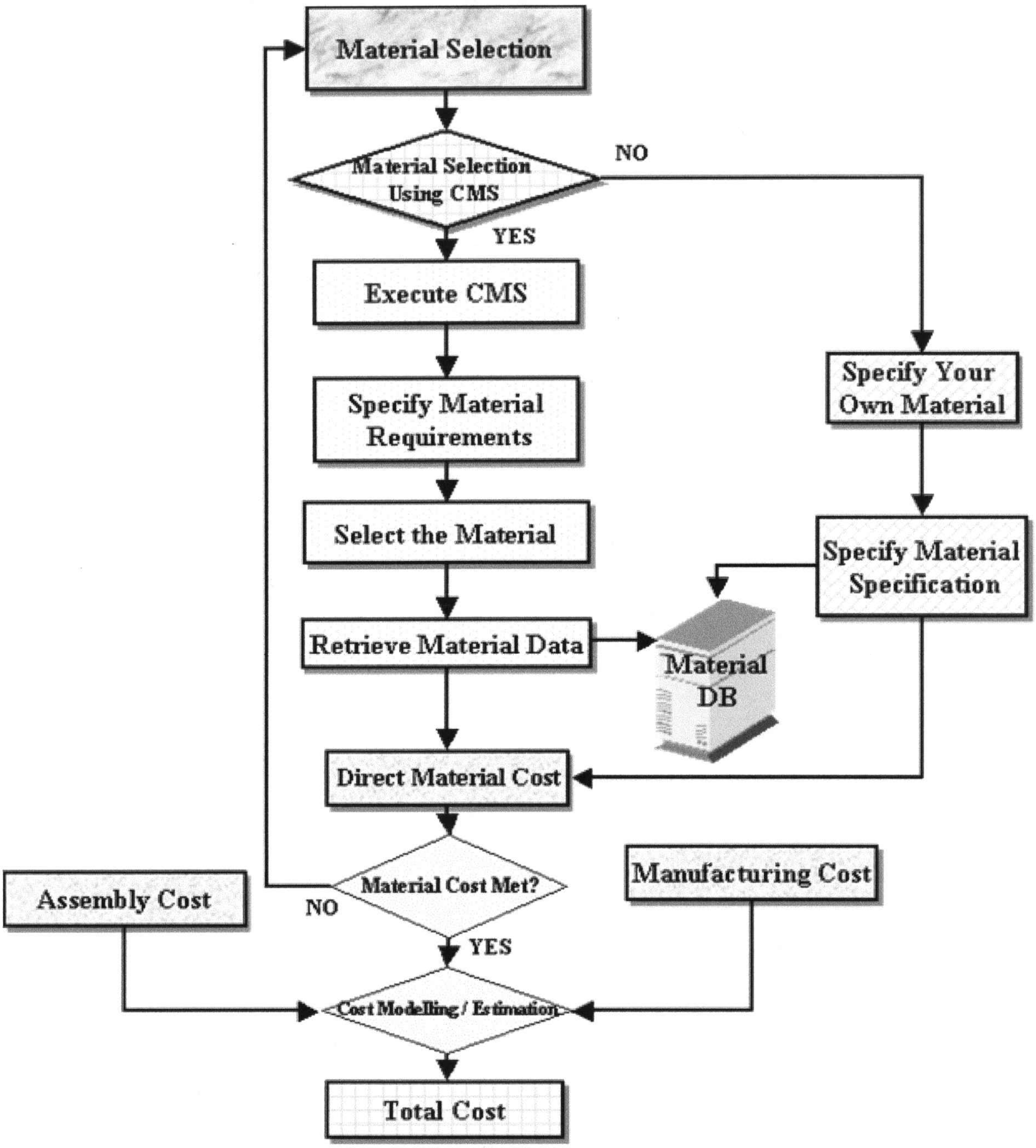


Fig. 2 Material selection/costing module

machining processes, injection moulding process and design for assembly. More than 800 rules have been established in this research. These rules were formulated and used to link objects or instances and have the following format:

$$IF \quad < antecedent_{(l)} > \quad < antecedent_{(n)} >$$
$$THEN \quad < consequent_{(l)} > \quad < consequent_{(m)} >$$

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.

2.3 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 approaches. The proposed system was developed using the relational database approach which in turn comprised 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 a feature specification database, is updated as a result of running the system. The databases in the system consist of five separate groups of databases: feature database, material database, machinability database, machine database and mould database. More details about these databases are set out in Section 3.1.

2.4 User interface

The user interface has 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 by which he/she forms an initial impression. A user-friendly interface (Fig. 3) has been developed, as an important part of the proposed system, in order to access the system easily and efficiently, even for a new user.

2.5 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. Further details of the various cost estimation techniques are explained in Section 3.5.

3 SYSTEM MODEL ARCHITECTURE FOR MACHINED COMPONENTS

The framework for cost modelling of machining processes consists of a feature-based CAD system, a material selection/costing module, a process/machine selection module, a manufacturing times module, cost estimation techniques and a user interface. The basic architecture

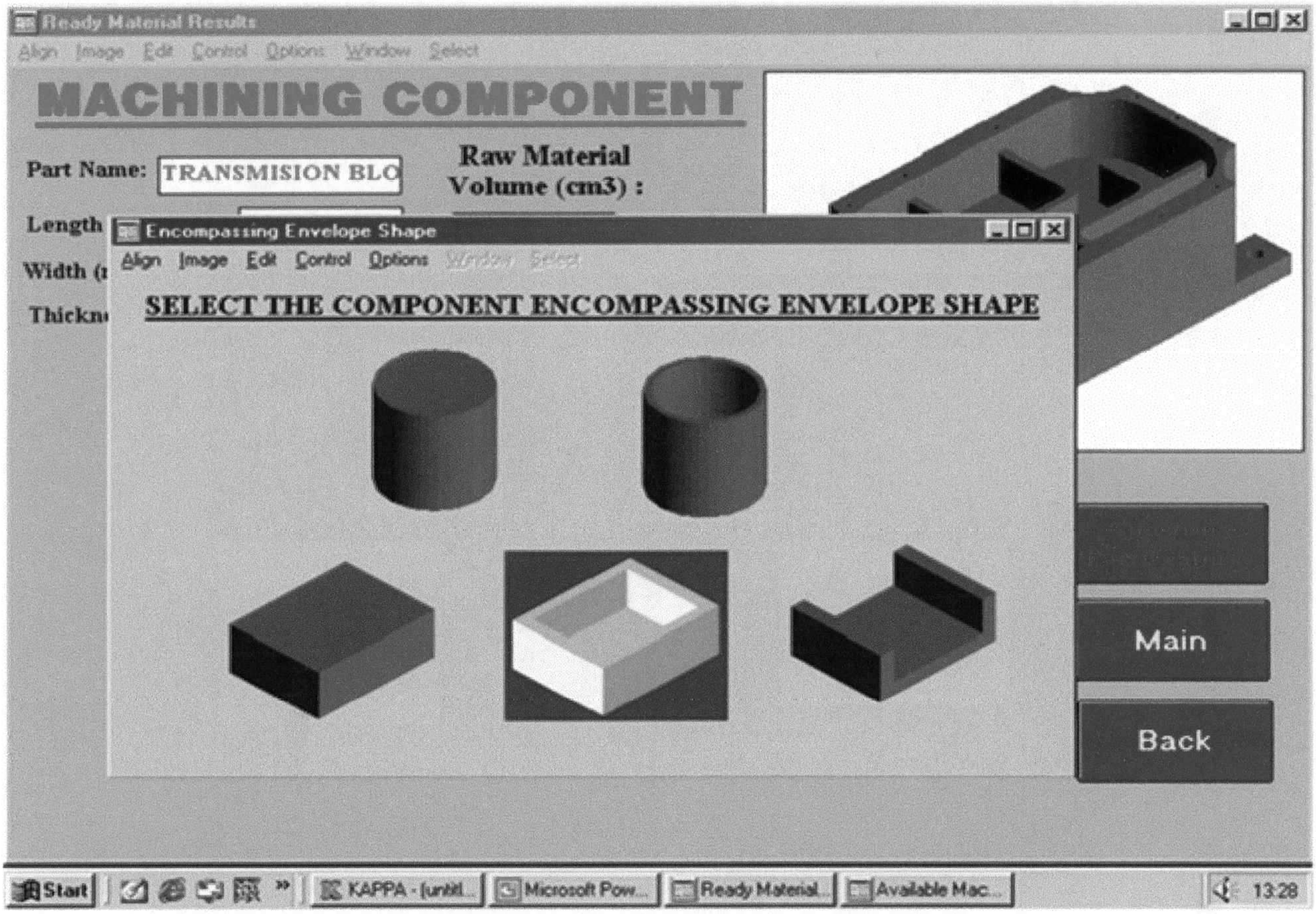


Fig. 3 Example of a user selection window

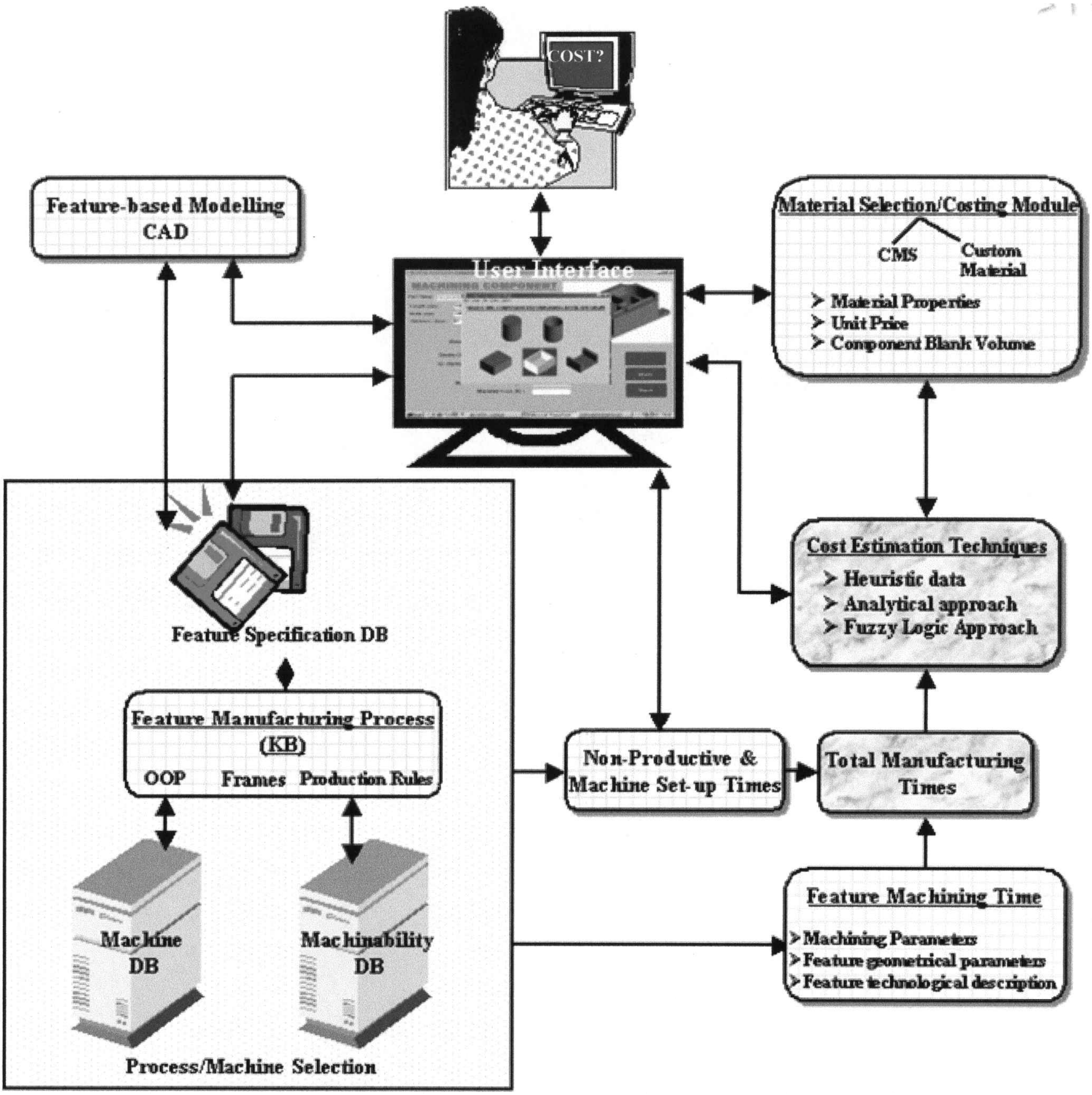


Fig. 4 Architecture of the cost estimation model for machining processes

of the system model of a machining product is shown in Fig. 4. The modules in the proposed system interact with one another.

The component model is constructed by the designer via the CAD system. The component 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 first step in the full analysis of a design concept is the selection of the best material to be employed. The system has the capability to retrieve automatically the necessary properties of a candidate material from Cambridge Materials Selector (CMS) software. The selection and optimization of machining parameters are carried out through a series of interactions between various modules including a feature specification database, a feature manufacturing process knowledge base, a machine database and a machinability database. The data used to identify each feature as well as the selected machining parameters are passed to the feature machining time function, in order to compute the required machining time for the feature. The final function is to

Table 1 Example of the feature specification database

Feature ID	Feature name	Feature type	Dimension type	Value (mm)	X distance (mm)	Y distance (mm)	Z distance (mm)	Tolerance (mm)	Surface finish (μm)
T5001	Thread	Internal	Diameter Pitch Thread 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

compute the manufacturing cost for each feature. 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 include the machining time for each feature, the non-productive time and the machine set-up time. Detailed descriptions of each component in the proposed framework are set out in the following sections.

Table 2 Sample of the machine tools database

Operation	Machine ID	Maximum surface finish (μm)	Minimum surface finish (μm)	Unit time cost (£/h)
LBM	L001	6.35	0.81	86.10
EDM	E001	6.35	0.81	30.03
Milling	M001	6.5	0.8	20.22
Drilling	M001	3.5	1.6	20.22
Drilling	D001	6.5	1.6	6.25
Boring	B001	0.4	0.4	6.25

3.1 Process/machine selection module

The process/machine selection module, as shown in Fig. 4, consists of a feature specification file, a machine specification database, a knowledge base of the feature manufacturing process and a 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 1 shows a sample file in 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 feature defined parameters include its identification number (ID), name, geometrical parameters such as its dimensions and location and technological parameters including 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. A sample of the machining tools database is illustrated in Table 2. The machinability database contains information on the machinability of the work material, the Brinell hardness, the recommended cutting speed and the feed rate. The machine data and machinability are obtained from machining data handbooks (e.g. references [**25**] and [**26**]). Table 3 shows a sample of the machinability database for the rough milling

Table 3 Sample of the machinability database

Material name	Material ID	Hardness HB	Depth of cut (mm)	Cutting speed (m/min)	Feed/tooth (mm)
Grey cast iron	MFECGG£££	120	3.8	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	MALW£££	30	6.35	304.80	0.559
alloys (wrought)		150	0.64	274.32	0.254

operation. The feature manufacturing knowledge base contains the manufacturing processes required to produce certain features with different surface finish and tolerance requirements.

3.2 Machining time modules

Machining operation 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 set-up time, the lower is the machining cost. Therefore, the total manufacturing cost is computed by adding the machining cost, the material cost and the 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 reference [**27**] and is based on the thread pitch and workpiece material. The machining time is calculated on the basis of 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 (e.g. references [**25**] and [**26**]) 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 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 will 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 the machining time for each feature, the non-productive time and the 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.

3.3 Feature-based modelling (FBM)

Feature-based modelling (FBM), sometimes referred to as feature technology, describes a product as the aggregation of features and feature relationships. However, a feature is defined as a generic entity that possesses product information that 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 a certain machining process has an important effect on generating a process plan. In this analysis, manufacturing form features were selected as the linchpin 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 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 slot is a form feature defined by its geometrical parameters such as its dimensions and location. The technological parameters include the dimension tolerance, the surface finish of the feature and the material property requirements. 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.

3.4 Approaches to knowledge-based representation

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

3.4.1 Object-oriented knowledge representation

Using the object-oriented technique, design, manufacturing and costing objects, such as machine tools, cutting tools, features and material properties, are organized into various classes represented in hierarchies. Figure 5 shows object-oriented representation of machining features. A class has a name and several subclasses, consisting of a number of objects with a number of slots and 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 the object-oriented technique is to take advantage of its characteristics of data abstraction,

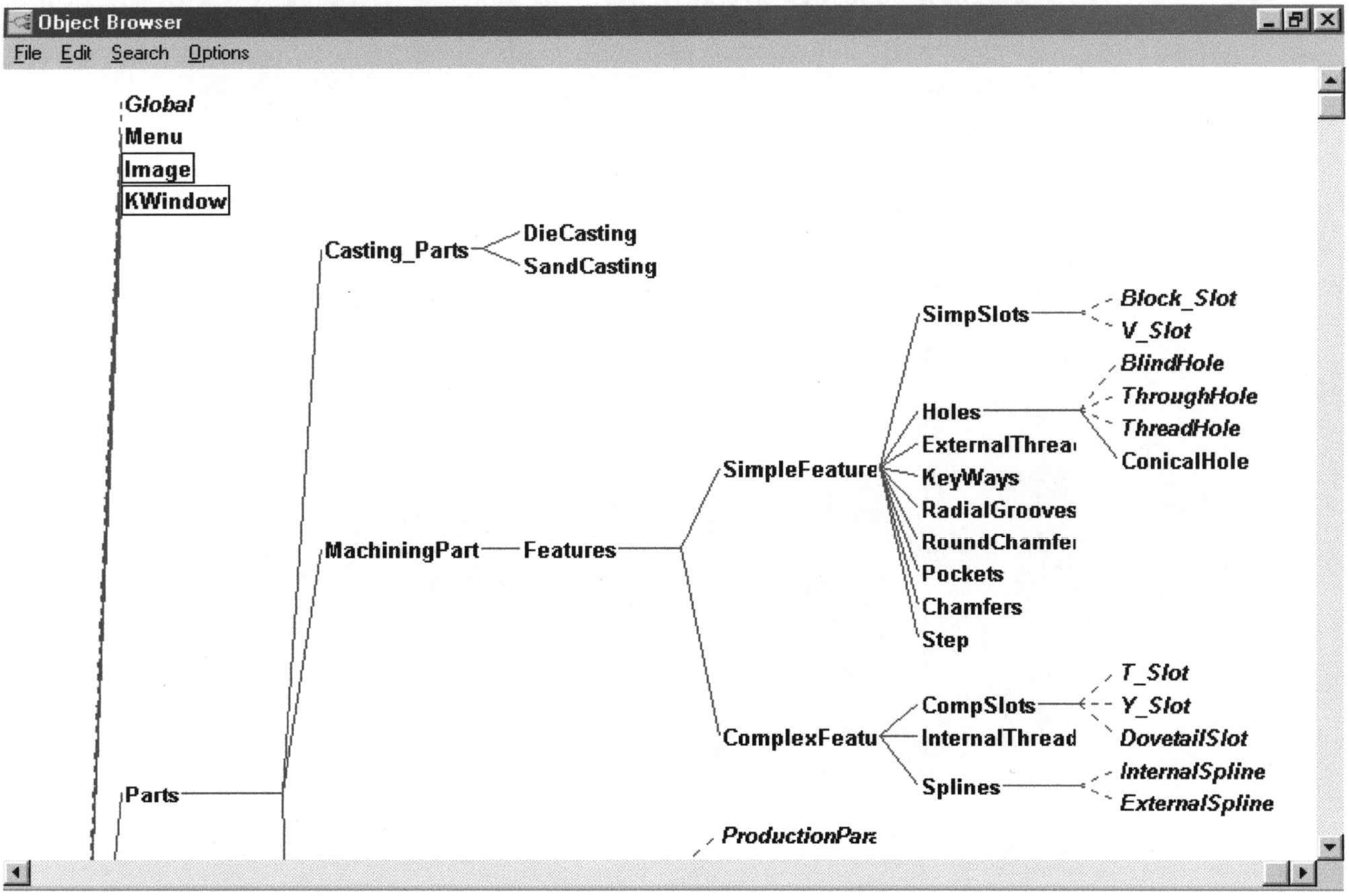


Fig. 5 Object-oriented representation of machining features

inheritance and modularity. Inheritance enables the designer to define a specific value into a higher class, and each can be inherited by the lowest class of the hierarchy.

3.4.2 Frame-based knowledge representation

A frame is described as a structure for storing interconnected information about a design and an object. It is a very effective means of knowledge representation of stereotypical objects. A 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 frames in Kappa-PC [**28**] 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.

3.4.3 Production rules knowledge representation

Knowledge and facts about a problem domain can be represented as a rule in the form *If* premises *Then* conclusion. The knowledge base of the developed system has 800 rules for process selection and design for assembly. For example, the selection of the appropriate operation to produce 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 minimum surface finish of the pocket <6.35 μm) *AND*
(Additional rules)
Then
(E001 is selected)

E001 is an electric discharge machine (EDM) used for producing sharp corner pockets.

Hole_Making_Rule1
If
(The feature is a hole) *AND*
(The diameter of the hole >3 mm) *AND*
(The aspect ratio 'depth over diameter' <8) *AND*
(The minimum tolerance of the hole >0.0125 mm) *AND*
(Additional rules)
Then
(M001 is selected) *AND*
(Drilling is selected process)

M001 is a computerized numerically controlled (CNC) milling machine.

Slot_Making_Rule1_1
If
(The feature is a slot) *AND*
(The width of the slot >4 mm) *AND*
(The minimum tolerance of the slot >0.01 mm) *AND*
(Additional rules)
Then
(M001 is selected) *AND*
(RoughMilling is selected process)

Slot_Making Rule1_2
If
(The feature is a slot) *AND*
(The RoughMilling is done) *AND*
(The surface finish for the slot base $\geqslant$*0.8 μm)* *AND*
(The surface finish for the slot base $\leqslant$*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 $\geqslant$*0.8 μm)* *AND*
(The surface finish for the slot wall $\leqslant$*6.5 μm)* *AND*
(Additional rules)
Then
(M001 is selected) *AND*
(EndMillingWall is selected process)

3.5 Cost estimation techniques

3.5.1 Algorithmic technique

The required machining time and cost for the component are computed on the basis of the methodology developed by Ou-Yang and Lin [**5**]:

1. Computation of the required machining time for each operation:

$$T_{ij} = k_j \prod_{k=1}^{n} p_{ijk} \tag{2}$$

where
T_{ij} = time required to accomplish machining operation j of feature i
k_j = coefficient for operation j
p_{ijk} = 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:

$$C_{ij} = M_h T_{ij} + S_h \tag{3}$$

where
C_{ij} = estimated machining cost for operation j of feature i
M_h = unit time cost (£/min) for machine 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:

$$\text{FC}_i = \sum_j C_{ij} \tag{4}$$

where FC_i is the estimated machining cost for each feature i.

4. Computation of the required machining cost for each component:

$$\text{TC} = \sum_i \text{FC}_i \tag{5}$$

where TC is the estimated machining cost for the component.

The total manufacturing cost is computed by adding the machining cost, material cost and set-up and non-productive costs.

3.5.2 Fuzzy logic approach

By applying the fuzzy logic approach to cost estimation, it is possible to handle the uncertainty in cost estimation problems that cannot be addressed by the traditional techniques. 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.

A fuzzy logic technique is applied in the developed system. The objective of this model is to overcome the uncertainty in the cost estimation model. In order to explain the steps in developing a fuzzy model, an example of a fuzzy logic system capable of estimating the machining time of a drilling hole is presented. The main factors affecting a feature cost are feature geometrical attributes as well as the required surface finish. The input variables are hole diameter, hole depth and surface finish, while the output variable is the machining time. Figures 6 to 9 show the fuzzy sets of the input and output variables. Fuzzy sets for hole diameter and hole depth are small (SM), medium (ME) and large (LA). Linguistic variables for surface finish are texture (TE), polish (PO) and normal (NO), while membership functions for machining time are low (LO), average (AV) and high (HI).

A decision table is a symbolic way of representing the logical interdependence between events. Decision tables, which 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

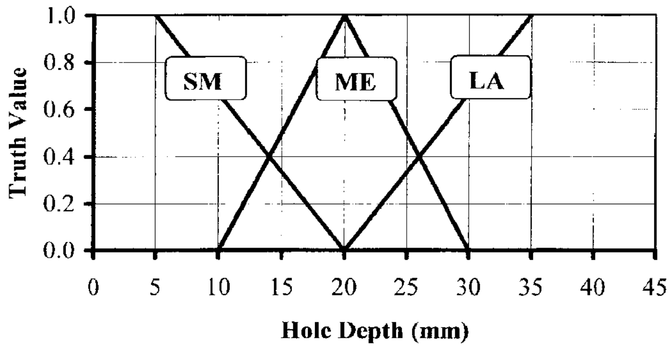


Fig. 6 Fuzzy sets for component volume

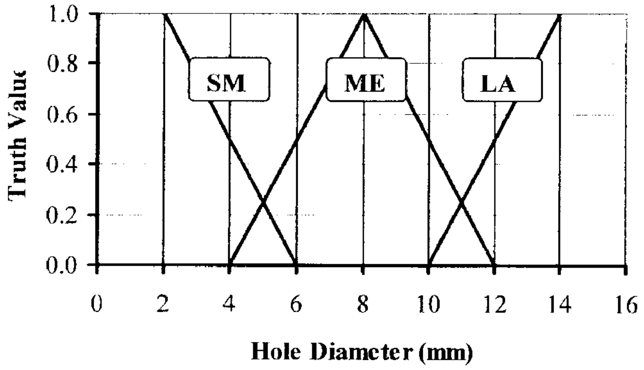


Fig. 7 Fuzzy sets for hole diameter

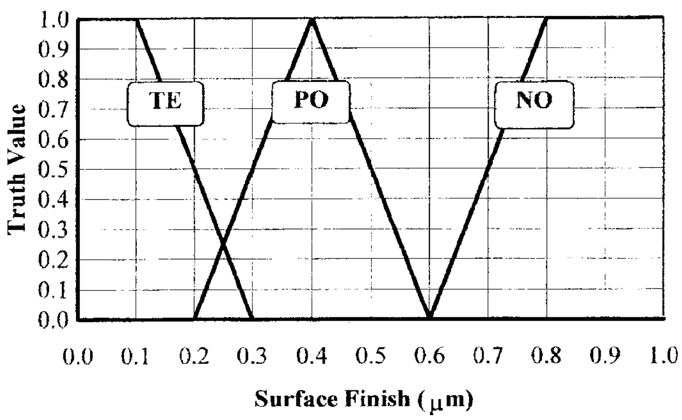


Fig. 8 Fuzzy sets for surface finish

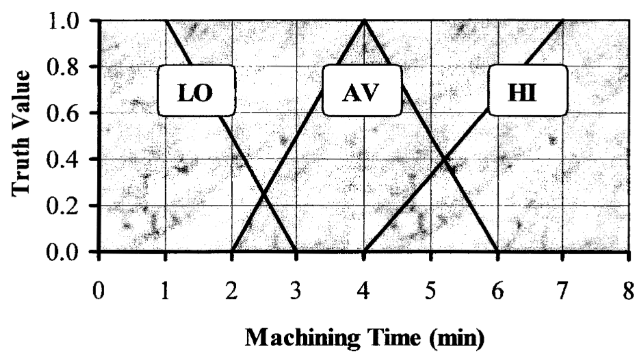


Fig. 9 Fuzzy sets for machining time

Table 4 Sample of a decision table for hole making

Hole depth	Small	Small	Large
Hole diameter	Small	Medium	Medium
Surface finish	Normal	Normal	Polish
Machining time	Low	Low	High

model, with three independent variables each consisting of three membership functions, a decision table with 27 rules is constructed. A sample of a decison table for hole making is illustrated in Table 4. The set of rules from the above decision table are:

Hole_Rule1
If
(The hole depth is small) *AND*
(The hole diameter is small) *AND*
(The required surface finish is normal)
Then
(The machining time is low)

Hole_Rule2
If
(The hole depth is small) *AND*
(The hole diameter is medium) *AND*
(The required surface finish is normal)
Then
(The machining time is low)

Hole_Rule3
If
(The hole depth is large) *AND*
(The hole diameter is medium) *AND*
(The required surface finish is polish)
Then
(The machining time is high)

The machining cost, C_m, of any feature is equal to the unit time cost, R_i, multiplied by a corresponding machining time, T_i:

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

3.6 System scenario for costing machined components

The scenario for machined component cost estimation is launched by specifying the production data, which enable the system to select the most economical 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 are presently under development.

The designer constructs the component model via the CAD system. The component envelope dimensions and volume are then retrieved from the database in the CAD system. The system prompts the users to select between specifying the material and its properties, based on their own criteria, or running 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 its 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 are stored in a feature specification file. The system examines the manufacturability

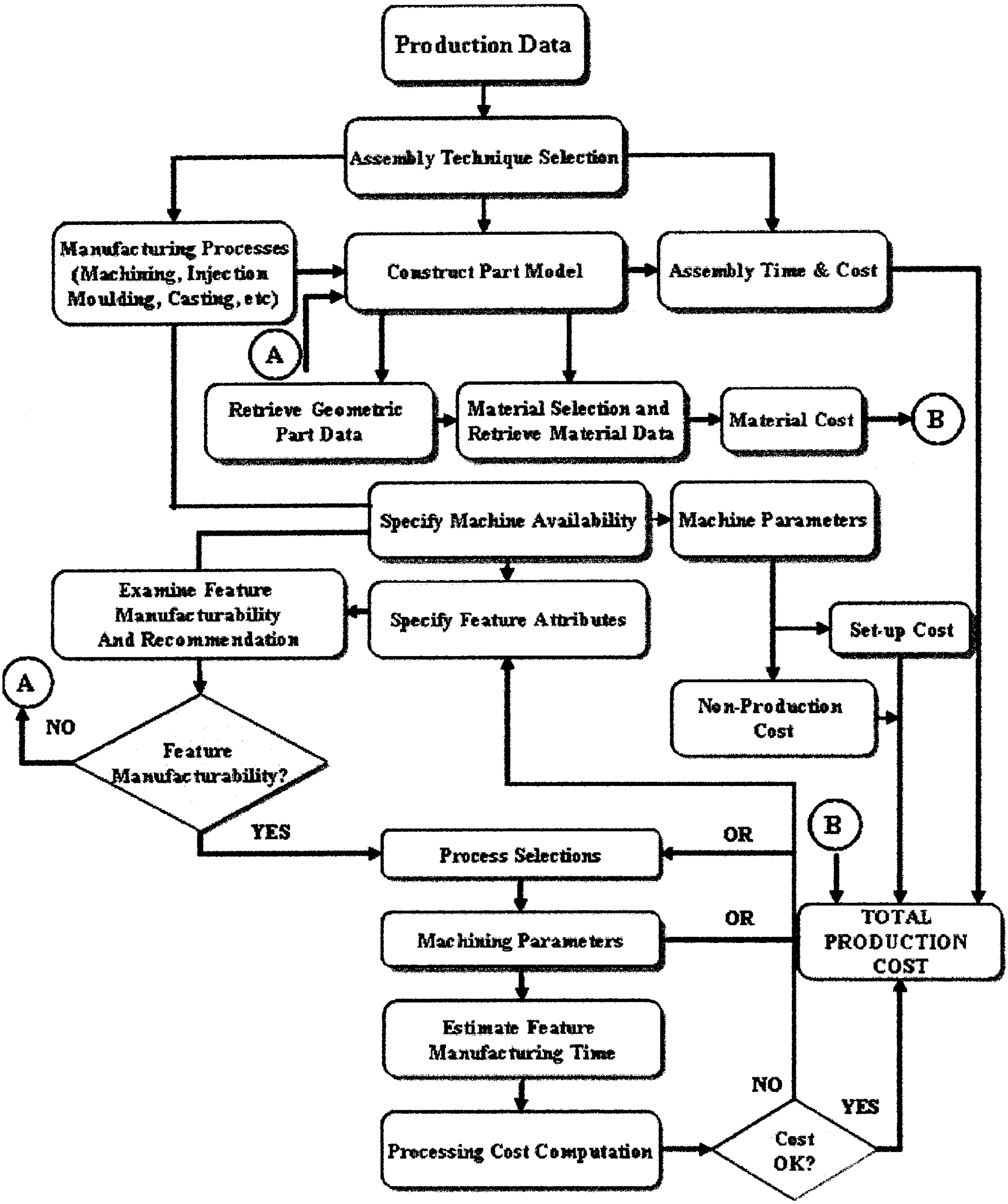


Fig. 10 System scenario for the machined component cost analysis process

of each feature by applying the manufacturing process rules stored in the knowledge base. Hence, for each process the system acquires a group of suitable machines from the machine database. From these appropriate machines, the system selects one that will provide a surface finish and tolerance range meeting the required specification of the specific feature. On the basis of 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 are produced and stored in the manufacturing cost module. The flow chart of the proposed cost analysis process is shown in Fig. 10. The system enables users to select another component for cost estimation. Finally, the system estimates the assembly cost of the product on the basis of the recommended assembly technique.

4 SYSTEM IMPLEMENTATION AND VALIDATION

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 advantage features of this system is that it warns users of features that are costly and difficult to manufacture with the available manufacturing resources. 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 unnecessary downstream manufacturing costs, thus reducing the total product cost and product lead time.

In order to validate the proposed system, two case studies were used to demonstrate the capability of this system. More case studies are mentioned in reference [**23**]. A scientific calculator was subjected to analysis of its design by the developed system: the system recommended the most economical assembly technique for the product; based on this recommendation, the system estimated the assembly time and cost required for assembling the calculator.

In addition, a sample of machined component (transmission transfer block) was chosen to compute the manufacturing cost by the system. 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 the University.

4.1 Case study 1: design analysis of a scientific calculator for assembly

The designer should be aware of the nature of assembly processes and should always have sound reasons for requiring separate components, and hence higher assembly costs, rather than combining several components into one manufactured item. The developed system has the capability to recommend the most economical assembly technique in the early stages of the design process. An exploded diagram in solid modelling representation of the scientific calculator is illustrated in Fig. 11. According to the design product analysis and the production parameters (production volume, number of components, etc.), the system recommended the robotic assembly system as the most economical assembly technique for assembling the scientific calculator. Figure 12 shows the system output for the recommended assembly technique. After appropriate assembly technique selection for the calculator, the system begins to estimate the cost of assembly by analysing the product design. The procedures for assembly technique selection and assembly cost estimation are detailed in reference [**23**]. The design analysis of the calculator components for robotic assembly was carried out through various assembly processes. These assembly processes, as shown in Fig. 13, include difficulty of component placement, direction of assembly and difficulty of insertion. The following are the main specifications of the robot system that are input to the system and used to estimate the assembly cost of the present case study:

(a) the cost of a standard assembly robot with controls, sensors, etc.: £50 625;
(b) the number of stations on the multistation system: 5;
(c) the standard gripper cost: £3125;
(d) the robot basic operation time: 3 s;
(e) the cost of one station on the free transfer machine, including buffers and controls: £15 625;
(f) the cost of special work carriers associated with one station on a multistation system: £3125.

The multistation assembly system cost estimation report for the scientific calculator generated by the system is illustrated in Fig. 14. The feeding methods used for this analysis are:

(a) programmable feeder (PF),
(b) special-purpose feeder (SF),
(c) manually loaded magazine, pallet or component tray (MG).

4.2 Case study 2: a machined component

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. The component, as shown in

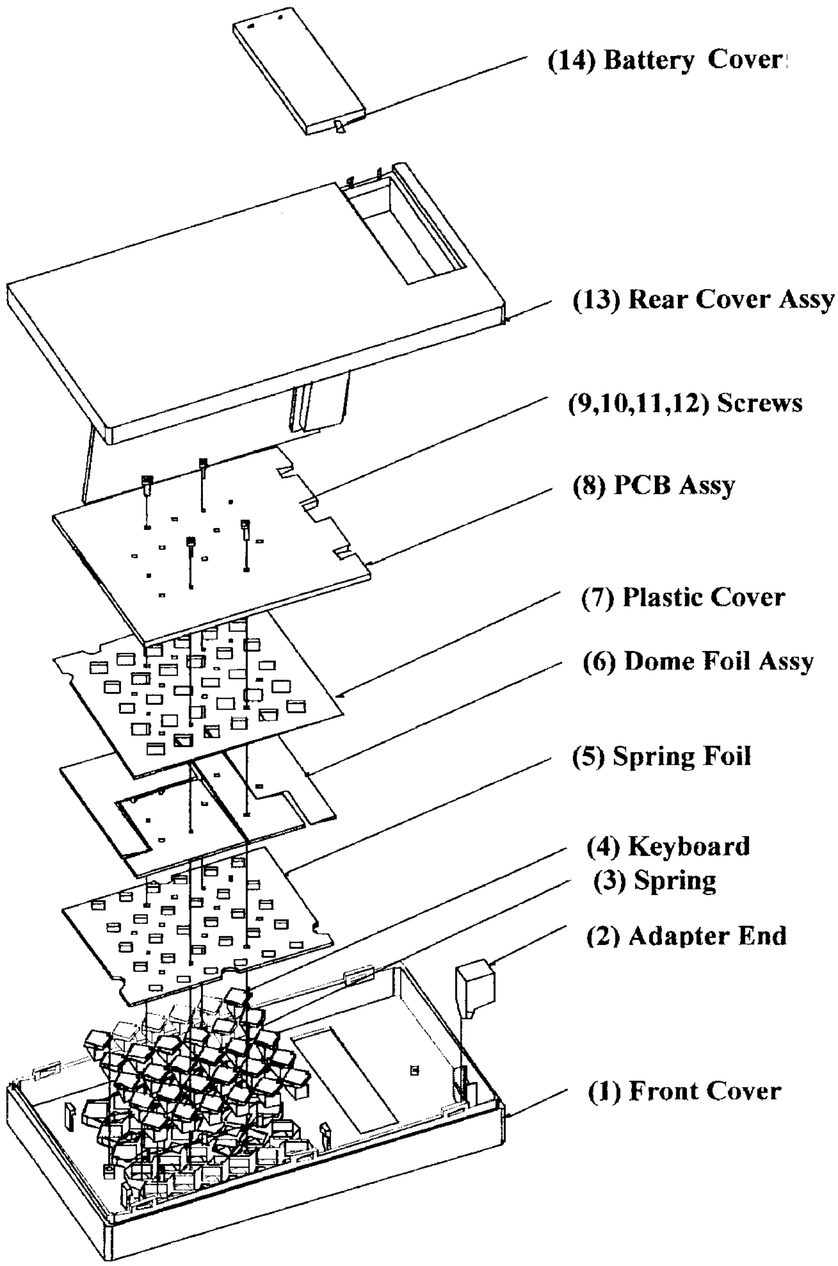


Fig. 11 Exploded solid modelling diagram of a scientific calculator

Fig. 15, contains five different kinds of feature: two through rectangular slots, 16 blind holes, four steps with round corners, four through holes, one tapping hole and ten rectangular pockets with round corners. Based on the functionality of the component, the user has to specify his own material or select a material from CMS. The properties of the selected material are saved as a data file to perform material properties extraction by the system. The material cost is estimated on the basis of the blank volume of the component. The estimated processing time for each feature is based on information such as 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 manufacturability criteria are considered for milling and drilling operations performed on a CNC milling machine. Non-traditional machines such as EDM and LBM were also considered. The total cost rate, C_T, of this machine can be obtained from the following equation:

$$C_T = C_L + C_M \qquad (11)$$

where C_L is the labour cost rate (£/h) and C_M is the machine cost rate (£/h).

The labour cost rate consists of the direct labour wage rate and overhead. The machine cost rate comprises the machine depreciation rate and the machine overhead. The depreciation rate is estimated on the basis of the working hours per year and amortization period. The machine overhead includes the cost of routine maintenance, the cost of unexpected breakdowns and services and the cost of factory space used.

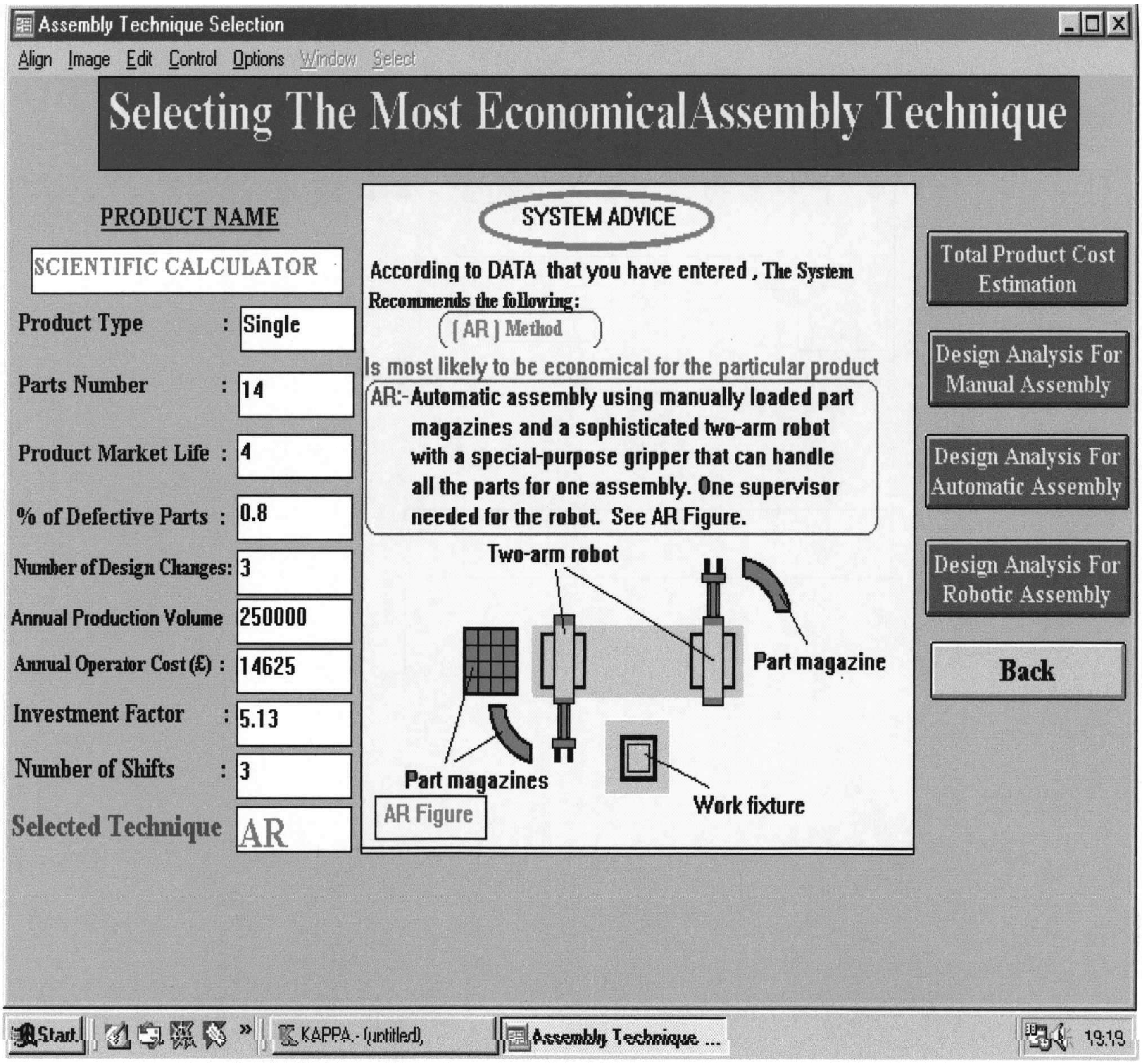


Fig. 12 System window of the appropriate assembly selection for the scientific calculator

The labour cost rate, C_L, can be estimated as follows:

$$C_L = \frac{\text{annual labour cost}}{\text{working hours per year}}$$

The machine cost rate, C_M, is calculated as follows:

$$C_M = \text{machine depreciation rate} + \text{machine overhead}$$
$$= \left(\frac{\text{machine cost}}{\text{working hours per year}}\right) \times (1 + \text{overhead})$$

The total machining cost rate of EDM is obtained from reference [**29**].

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, as shown in Fig. 16. The production parameters include the total annual labour cost and the working hours per year, while the machine parameters consist of machine cost, machine overheads and amortization period.

The cost estimation is based on a combination of the heuristic data and algorithmic technique previously addressed in Sections 3.4 and 3.5 respectively. In addition, a complete scenario for costing a machined component is presented in Section 3.6. Figure 17 illustrates the cost estimation report prepared by the system for the present case study. The feature-by-feature cost estimation that shows in the cost report is very useful for the user to indicate a specified feature with high processing cost. Consequently,

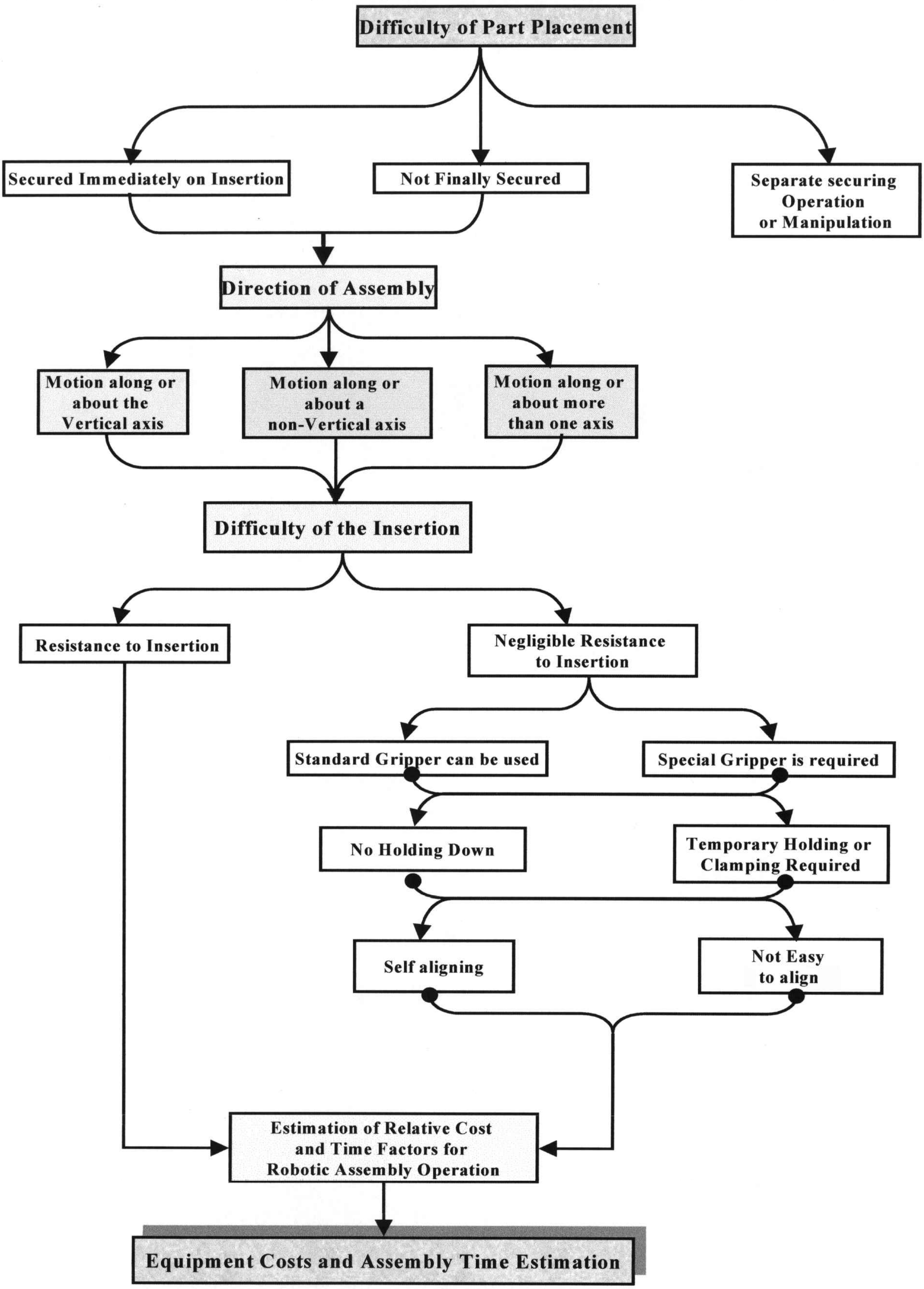
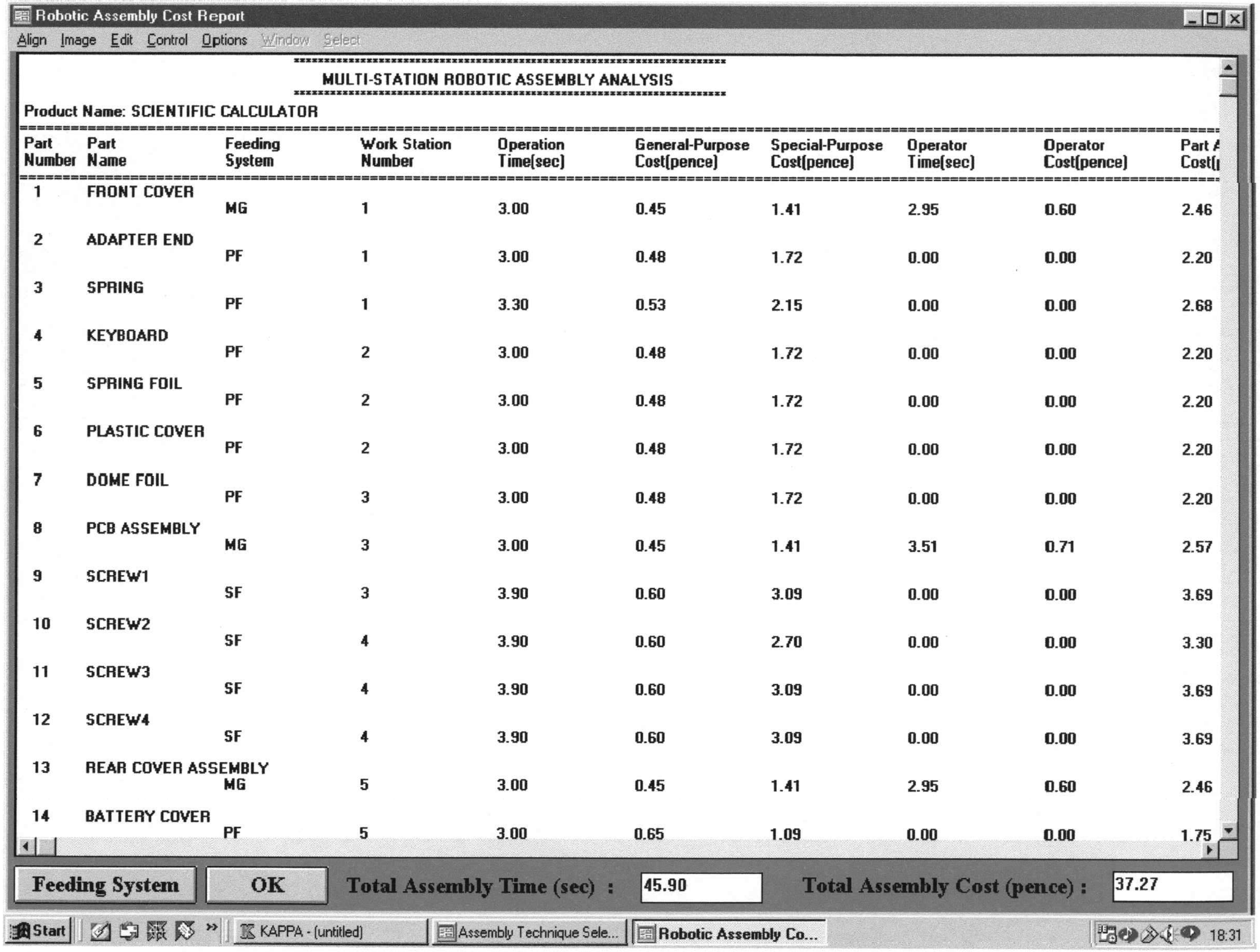


Fig. 13 Assembly processes used to estimate the robotic assembly system cost



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

Fig. 14 Multistation robot assembly cost estimation report for the present case study

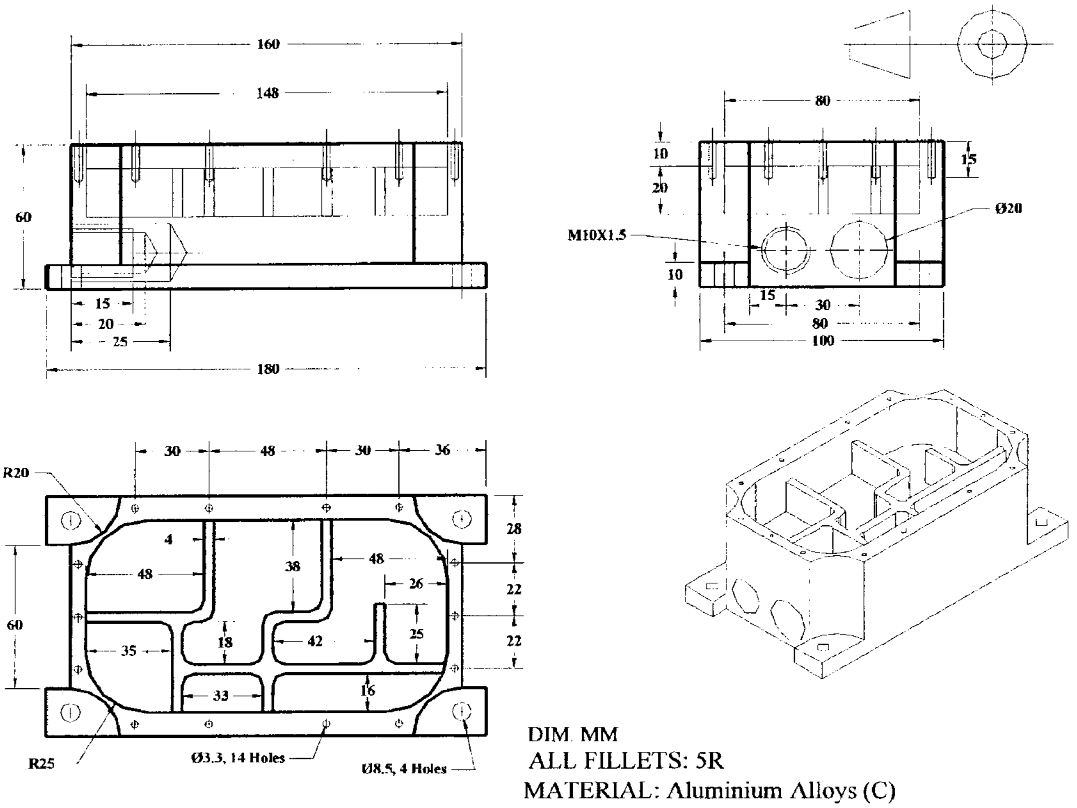


Fig. 15 Geometric representation of the transmission transfer block

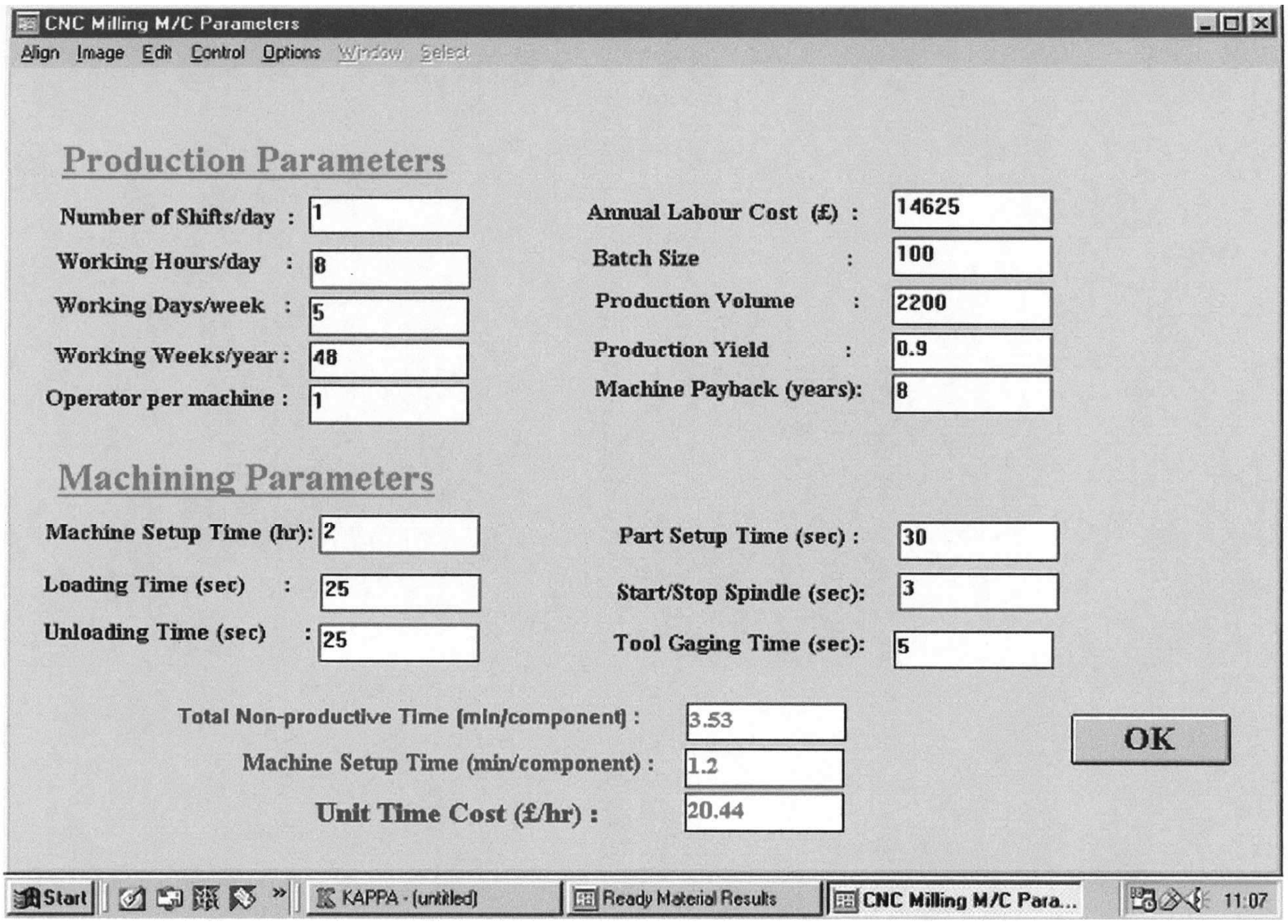


Fig. 16 Production and machine parameters for a CNC milling machine

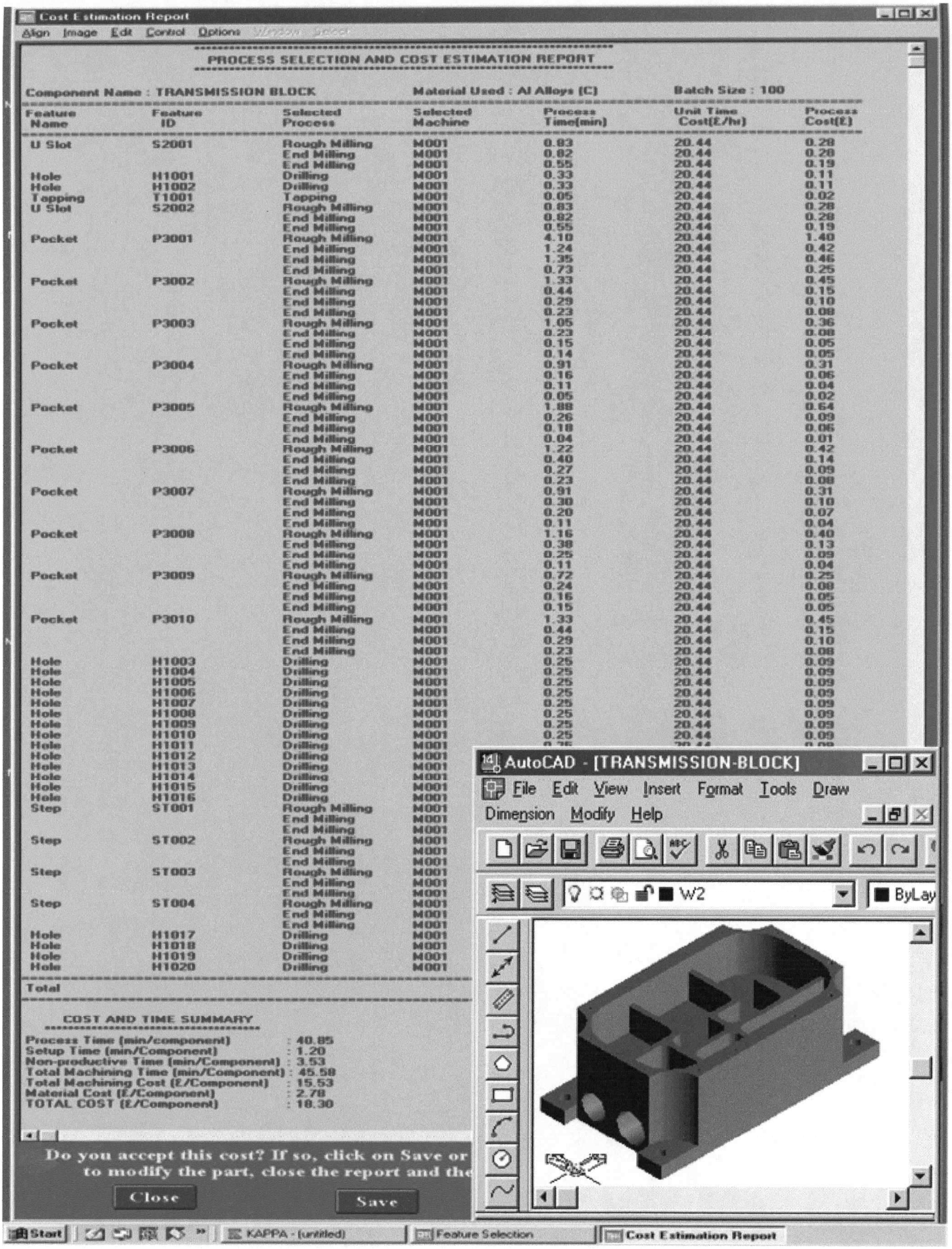


Fig. 17 Process selection and cost estimation report generated for the present case study

the user can adjust the design on the basis of the analysed results.

4.2.1 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. The comparison showed that cost estimated was almost 10 per cent less than the actual cost estimation since the system takes into consideration process optimization, design alternatives and design for assembly issues. This demonstrates the reliability of the developed system for cost estimation at an early design stage.

5 CONCLUSIONS

An object-oriented and rule-based prototype system for product cost modelling at an early design stage of the product life cycle has been described. The developed system comprises a CAD solid modelling system, a material selection module, a knowledge-based system, a process optimization module, a design for assembly module, a cost estimation module and a user interface. The system is integrated with material selection software to facilitate the material selection process.

A major achievement of this system is that it unifies cost modelling, process sequence, machinability and design for assembly into an integrated system. The developed system can be used in the early design stage, so redesign cost and a long lead time are avoided. A feature-by-feature cost estimation as well as the total product cost estimation report is generated 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. Cost, manufacturing and design knowledge have been efficiently represented by the use of various knowledge representation approaches such as OOP, production rules and frames to provide flexible, updateable and effective organization of the knowledge necessary for cost analyses.

A user-friendly interface consisting 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.

A combination of heuristics data, algorithmic approach and fuzzy logic techniques was implemented. The developed system allows users to generate accurate cost estimates for new designs and explore alternative materials and process. The developed cost effective design environment was evaluated on real products. Conclusions drawn from the system indicated that the developed prototype system could help companies reduce product cost and lead time by estimating the total product cost throughout the entire product development cycle, including assembly cost. Further research is currently being undertaken to model the costs of other manufacturing processes, such as sheet metal and casting processes, and make the system more comprehensive.

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