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An Intelligent Knowledge-Based System for Product Cost Modelling

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An intelligent knowledge-based system for product cost modelling is presented in this paper. The developed system has the capability of selecting a material, as well as machining processes and parameters based on a set of design and production parameters; and of estimating the product cost throughout the entire product development cycle including assembly cost. 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. Hybrid knowledge representation techniques, such as production rules, frame and object oriented are employed to represent manufacturing knowledge. Fuzzy logic-based knowledge representation is applied to deal with uncertainty in the knowledge of cost model to generate reliable cost estimation.

This paper deals with cost modelling of both a machining component and an injection moulding component, which is a process that gives high production rates, excellent quality and accuracy of products, and low manufacturing cost. Based on the analysis of the moulded product life cycle, a computer-based cost model was developed which integrated the relationship between cost factors, product development activities, and product geometry. The estimated cost included the costs of material, mould and processing. The system has been validated through a case study.

Keywords: Concurrent engineering, Cost modelling, Fuzzy Logic, Knowledge-based, Process optimisation

1. Introduction

One of the targets of concurrent engineering is to reduce both the cost and manufacturing time of a product through simultaneous consideration of product development activities. Research results showed that over 70% of the production cost of a product is determined during the conceptual design stage [1]. However, the design phase itself accounts for only 6% of the total development cost [1]. Therefore, devoting a greater effort to design cost is a necessary step towards optimising product costs. In general, cost-estimating approaches can be broadly classified as intuitive, parametric techniques, analogical models, and analytical models. However, the most accurate cost estimates are made using the analytical approach. 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.

Wei and Egbelu [2] developed a framework to estimate the lowest product manufacturing cost from the AND/OR tree representation of an alternative 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 [3] developed an expert system for the concurrent product and process design of mechanical parts. Their approach enabled designers to ensure that the product would be manufactured with existing manufacturing facilities to provide high quality and the lowest cost.

Rehman and Guenov [4] described a methodology for modelling manufacturing costs at the design phase of the life cycle of a product. In this system, the link between design knowledge and manufacturing knowledge is achieved through an advanced artificial intelligent architecture, i.e. a blackboard framework, for problem solving.

It is clear that this model cannot be used to generate an accurate manufacturing cost as it estimates the manufacturing costs without consideration of process planning. Gayretli and Abdalla [5] presented a prototype constraint-based system for evaluation and optimisation of machining processes. One of the evaluation and optimisation criteria for machining processes is the manufacturing cost.

Luong and Spedding [6] described the development and implementation of a generic knowledge-based system for process planning and cost estimation in the hole making process. A major feature of this system is that it unifies process sequence, machinability and cost estimation into an integrated system, which caters for the requirements of small to medium-sized companies, involved in batch production. Luong and

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Spedding's system lacks an interface to a CAD system, and the capability of process plan optimisation.

Allen and Swift [7] developed a technique that can 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.

Ou-Yang and Lin [8] developed an integrated framework for feature-based manufacturing cost estimation at an early design stage. Their system estimated the manufacturing cost of a design according to shapes and precision of the features. 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 the manufacturing costs of prismatic components.

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 [9].

Sheldon et al. [10] 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 cost information that was provided by a cost accounting system, to establish the appropriate cost structures suitable for different groups of DFC users.

Geiger and Dilts [11] developed a conceptual model and working prototype of a new application for blending product design and cost accounting, for automated design-to-cost. The model integrates manufacturing and accounting concepts for feature-based modelling, group technology, computer-aided process planning, and activity based costing. Hayes and Sun [12] developed technologies that enabled the construction of design tools which generated cost-reducing design suggestions automatically, by identifying those areas of the design that were most cost-critical. Identifying those cost-critical areas requires an in-depth understanding of how the design will lead to manufacture. They used a program called the Manufacturing Evaluation Agent to produce cost-reducing design suggestions.

Feng et al. [13] presented a mathematical model as well as an algorithm to determine the minimum cost design. This cost evaluation was based on features. The machining time (cost) of a component depended on the time of performing operations and the changeover and set-up time. In general, the changeover and set-up time were the most significant components of machining time, which implied that the shorter the changeover and the set-up time, the lower the machining cost. Operation-based cost models were one of the earliest attempts in estimating manufacturing costs. Because of the type of information required, these models could be used effectively only in the final design stage.

Shing [14] described the procedures for estimating rapidly the approximate manufacturing cost of a moulded component through the use of a computer program, developed specifically for this task. This system depended on the mathematical equation to estimate the manufacturing cost of an injection-moulded component. The estimated cost included the costs of material, mould, and processing.

McIlhenny et al. [15] developed software for the cost estimation model of injection moulded components. In this model, certain factors such as the material cost and maintenance cost were included in addition to the mould base and process cost. Assembly cost estimation was one of the criteria used to determine the most economical assembly technique for a product [16].

The above literature review shows that a number of cost models have been developed for various kinds of application, but little effort was made in cost modelling at an early stage of the entire product development cycle. The major limitations of these systems were that most of them were mainframe based, were expensive, and required a long learning curve. They 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 this, an integrated framework PC-based system for product cost modelling to achieve several objectives is presented. First, a methodology for modelling manufacturing costs during an early design stage is developed. Secondly, the proposed system provides an environment that assists inexperienced users in estimating the manufacturing cost of a product. Finally, it advises users on how to eliminate design and manufacturing related conflicts that may arise during the product development cycle.

To achieve the above objectives, two major steps were undertaken:

Construction of a knowledge-based system (KBS) for cost modelling.

Integrating the KBS with both a material selection database and a CAD system.

2. Knowledge-Base Approach to Cost Modelling

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. 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 with the available manufacturing resources.

Past studies have shown that the proportion of assembly cost could be as high as 50% of the total manufacturing cost [17], in the case of many mechanical and electrical assemblies. Therefore, the proposed system enables designers to estimate the total product cost including the cost of the assembly operations. The assembly cost will depend on the assembly technique that the system suggests to the user.

The proposed framework system is composed of two main modules: cost modelling of a machined component, and cost modelling of an injection moulded component. The prototype system is developed with the attributes of a well-engineered software system in mind, such as maintainability, reliability, and efficiency [18]. The system is designed to provide users with the option of either running the entire integrated system or operating the individual modules separately. Discussion of each module is given below.

3. Cost Modelling of Machining Components

To obtain an appropriate estimation of the manufacturing cost, an initial process plan should be used. Initial process planning includes generation and selection of machining processes, their sequence, and their machining parameters. The machining parameters comprise cutting tool type and cutting conditions (e.g. feedrate and cutting speed). This ensures that 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 machining component consists of a feature-based CAD system, material selection, process/machine selection, a user interface, and cost estimation techniques. The basic structure of the system is shown in Fig. 1. The modules in the proposed system interact with one another.

A model of the component 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 must 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 of the product by running Cambridge Material Selection (CMS) software, Granta Design Ltd [19] and retrieve the necessary data on the selected material, or to specify the material based on the user's own criteria. The material properties are forwarded to the cost estimation module, so that the material cost

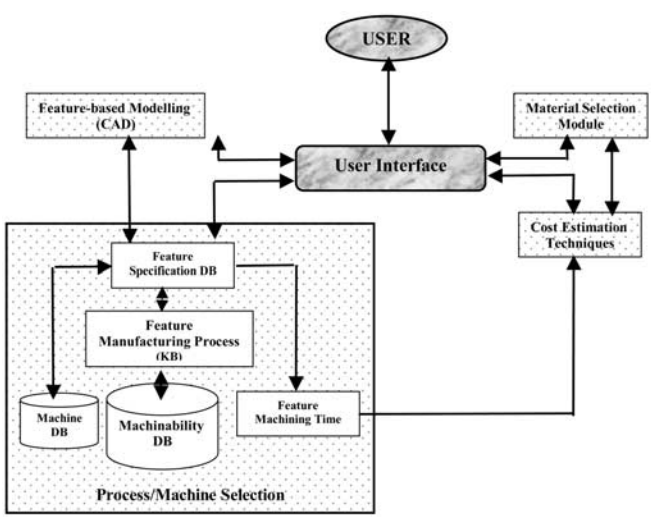

Fig. 1. The architecture of the proposed cost estimation of machining components.

can be computed. The selection and optimisation of machining parameters are carried out through a series of interactions between various modules including the feature specification database, feature manufacturing process knowledge base, 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 final function is to compute the manufacturing cost for each feature. The data required to perform this task are the manufacturing time for each feature and the unit time cost of the assigned machine from the machine database. Detailed descriptions of each component in the proposed framework are set out in the following sections.

3.1 Process/Machine Selection

The process/machine selection module, as shown in Fig. 1, consists of a feature specification file, a machine specification database, a knowledge base of the feature manufacturing process, a machinability database, and a feature machining time function. The proposed system contains two types of database: permanent (static) and temporary (dynamic). 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 is a feature specification database is updated as a result of running the system. 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 machining specification database stores related data on the available machines, the kinds of operation 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 machine tools database is illustrated in Table 2. The machinability database contains information on machinability of the work material, Brinell hardness, recommended cutting speed and feedrate. The machine data and machinability are obtained from machining data handbooks (e.g. [20] and [21]). Table 3 shows a sample of the machinability database for rough milling operation. The feature manufacturing knowledge base contains the manufacturing processes required to produce certain features with different surface finishes and tolerances.

The feature machining time function is used to estimate the required manufacturing time for each feature. The machining time is calculated, based on the material removal volume and specified surface roughness of each feature. The estimated machining time is used to compute the machining cost of the component. Then, the computation results for machining time and cost estimation are prompted to the user.

3.1.1 Feature Representation

A product can be represented by the aggregation of features and feature relationships. A feature is a generic entity which possesses product information, which may be used for design

Table 1. An example of the feature specification database.

Feature ID	Feature name	Feature type	Dim. type	Value (mm)	X_dist. (mm)	Y_dist. (mm)	Z_dist. (mm)	Tolerance (mm)	S_Finish (μm)
H1001	Hole	Blind	Diameter	15	95	40	0	0.01	0.2
			Depth	43					
S2001	Slot	Block	Length	82	80	23	0	0.01	0.8W
			Width	40					0.2B
			Height	35					
C4001	Chamfer	Through	Length	8.0	120	55	0	0.01	0.6
			Width	8.0					
			Height	65					
T5001	Thread	Internal	Diameter	15	95	40	0	0.01	0.1
			Pitch	2.00					
			T_Depth	1.5					
			Length	30					

Table 2. A sample of the machine tools database.

Operation	Machine ID	MaxS_Finish (μm)	MinS_Finish (μm)	UnitTimeCost ($ h^{-1})
EDM	E001	6.35	0.81	48.05
Milling	M001	6.5	0.8	33.14
Drilling	M001	3.5	1.6	33.14
Drilling	D001	6.5	1.6	10.00
Boring	B001	0.4	0.4	10.00

or communication in 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 and in a form that matches manufacturing knowledge. Analysis of the form features directly associated with certain machining processes, has an important effect on generating a process plan. In this analysis, manufacturing form features are the lynch pin for the generation of the machining processes and the 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 a topological and geometrical description of the component. For instance, a hole is a 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.

3.1.2 Knowledge Representation of Process Selection

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 be solved easily. Many representation techniques, such as production rules, object orientation, case base 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 work. These techniques, such as production rules, frames and object-oriented representations are described in detail as follows.

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,

Table 3. A sample of the machinability database.

Material name	Material ID	Hardness Bhn	Depth of cut (mm)	Cutting speed (m min^{-1})	Feed/tooth (mm)
Aluminium alloys	MALC_$$$	40	6.35	182.88	0.254
(cast)		100	1.27	243.84	0.305
Steel,	MFECSLC$$$	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

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 premiss 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:

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)

E001 is an electric discharge machining (EDM) that is used for producing fine holes.

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)

Frames. A frame is a data structure that describes multidimensional 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 the Kappa-PC expert system toolkit [22] are very flexible so that images and active values of any slots can be attached to monitor value changes. Facts as attributes of slots allow the description of values of a slot and how they are passed down the hierarchy.

Object-Oriented Representation. Object-oriented programming systems enable designers 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 2 shows the 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 feedrate, 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 the 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, each can be inherited by the lowest class of the hierarchy.

3.2 Material Selection

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 and complicated stage that is made early in the design process. There are many constraints for material selection, such as product functionality, material cost, and the type of manufacturing process. The system prompts the user to choose between two options for the material selection (see Fig. 3). The first option is that users select and specify the material based on their own criteria. The second option is that the system executes CMS software [19]. 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, e.g. 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. A materials selection chart is generated by CMS as shown in Fig. 4. A material can be selected satisfactorily by specifying ranges for the previously selected material properties.

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 specification and unit cost of the material. The material cost (C_{mt}) can be estimated using:

$$C_{mt} = V\rho C_w \quad (1)$$

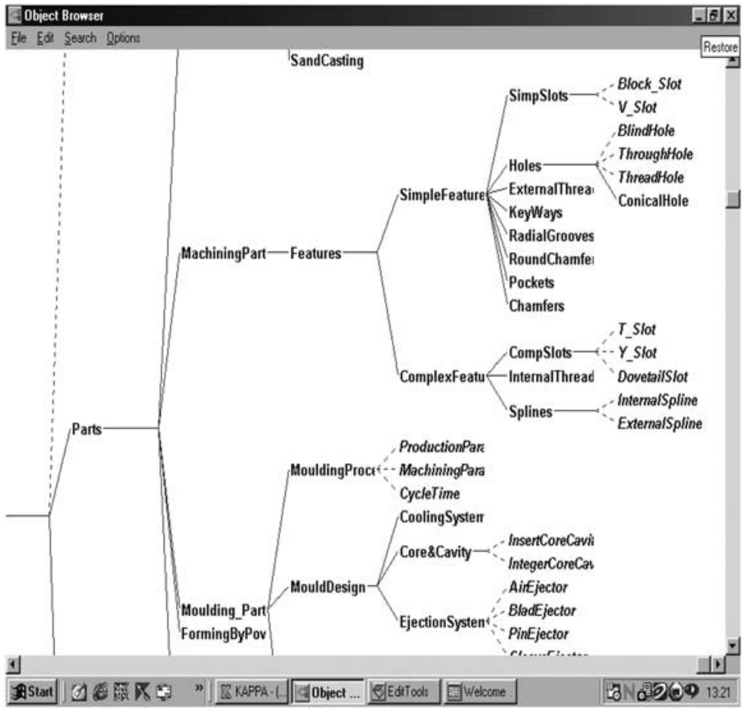

Fig. 2. An object-oriented representation of manufacturing processes, cost elements, and features.

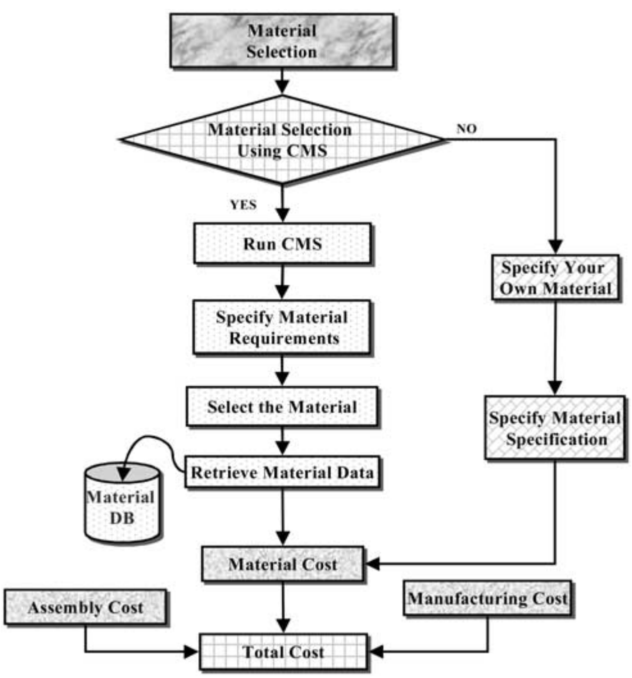

Fig. 3. The material selection flowchart.

where,

V = component volume, m^3

ρ = material density, kg m^{-3}

C_w = unit price, \$ kg^{-1}

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

3.3 User Interface

A user-friendly interface has been developed, as an important part of the proposed system, to provide the user with an interactive design environment, so that the system can be used 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 3D solid models, as well as with the CMS software. The retrieved component 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 that will 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 a hard copy of the system recommendations and reports, or quit the system altogether.

3.4 Cost Estimation Techniques

3.4.1 Algorithmic Technique

The required machining time and cost for the component are computed based on the methodology developed by Ou-Yang and Lin [8].

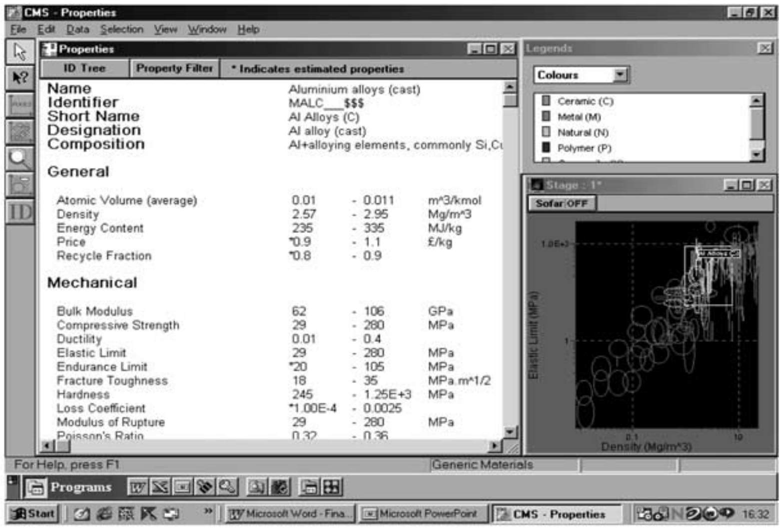

Fig. 4. The material selection chart and material properties within CMS (version 2).

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 the machining operation j of feature i

k_j = coefficient for the 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 the operation j of feature i

M_h = unit time cost (\$ min^{-1}) 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.

$$FC_i = \sum_j C_{ij} \tag{4}$$

where,

FC_I = the estimated machining cost for each feature i

4. Compution of the required machining cost for each component.

$$TC = \sum_i FC_i \tag{5}$$

where,

TC = estimated machining cost for the component

Set-up times for various machine tools were obtained from machining handbooks and were used to estimate set-up costs, in order to obtain a more accurate cost estimation [21]. The total manufacturing cost is computed by adding the machining cost, material cost, set-up and changeover costs.

3.4.2 Fuzzy Logic

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 [23]. 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 CERs. Fuzzy logic has been used as the basis for controlling industrial processes and consumer products. This is because it does not require the use of complex mathematical models. In the case of an expert system, production rules are used to characterise cost-estimating knowledge. Production rules capture knowledge in the form of "if…then…" statements. A fuzzy production rule is similar to the traditional type of production rule except that the conditions in the production rules are replaced with linguistic expressions to which truth-values are assigned. The first part of a fuzzy production rule is defined as a fuzzy set. The difference between a fuzzy expert system and the traditional expert system is that the reasoning process used to reach conclusions is different. No attempts have been made to estimate the cost for a complex feature that has more than two cost drivers. A fuzzy technique is implemented in this system to deal with uncertain knowledge on cost estimation. Several steps are required to develop a fuzzy logic model. These steps are fuzzy sets of input variables and fuzzy sets of output variables. Each variable has a number of memberships. The main processes in the fuzzy model are fuzzification of inputs, fuzzy inference based on a defined set of rules, and, finally, defuzzification of the inferred fuzzy values. For this fuzzy technique, with three input variables

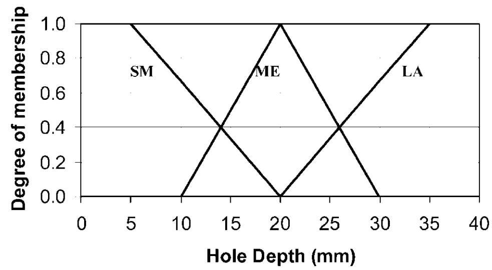

Fig. 5. The membership function for hole depth.

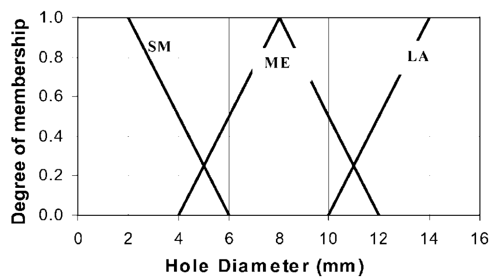

Fig. 6. The membership function for hole diameter.

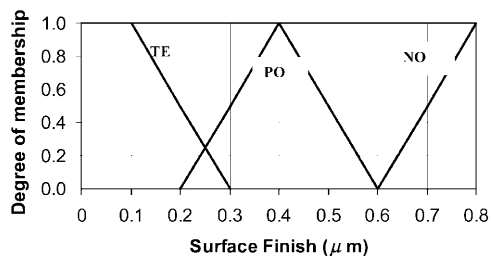

Fig. 7. The membership function for surface finish.

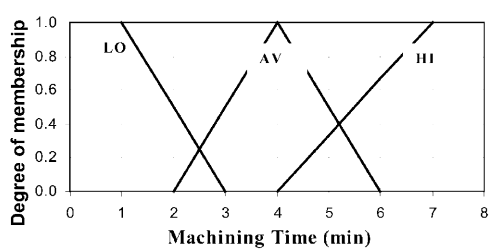

Fig. 8. The membership function for machining time.

each of which consists of three membership functions, a (3 × 3 × 3) decision table with 27 rules is constructed. 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 input variables are hole diameter, hole depth, and surface finish, whereas the output variable is the machining time. Figures 5, 6, 7, and 8 show the memberships of the input and output variables. Membership functions for hole diameter and hole depth are small (SM), medium (ME), and large (LA). Membership functions for surface finish are texture (TE), polish (PO), and normal (NO). Membership functions for machining time are low (LO), average (AV), and high (HI).

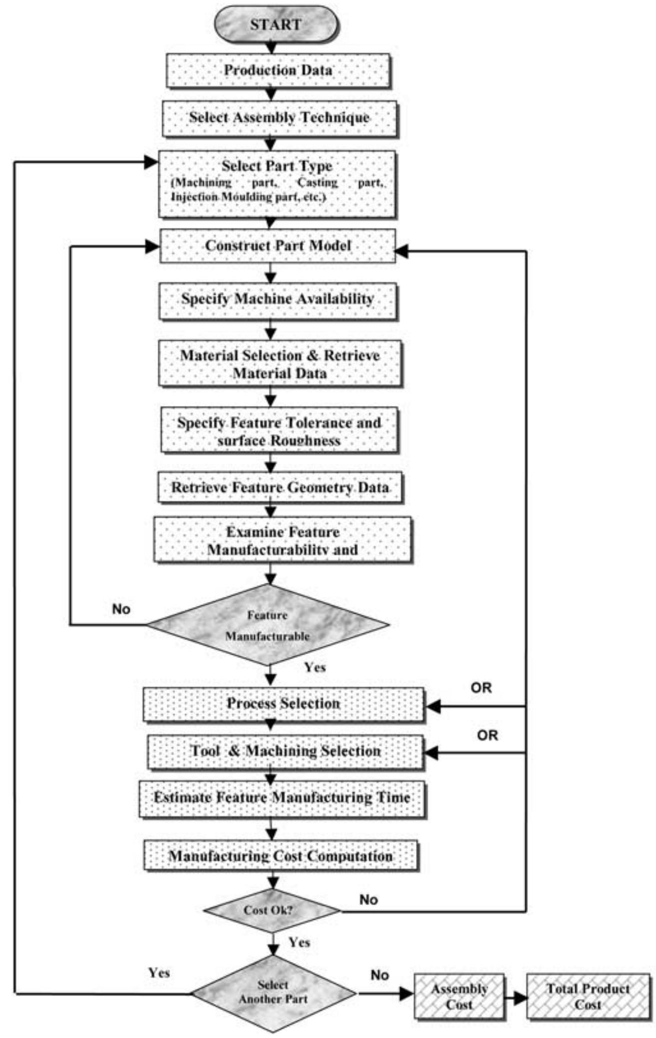

Fig. 9. The flowchart of the proposed cost analysis process.

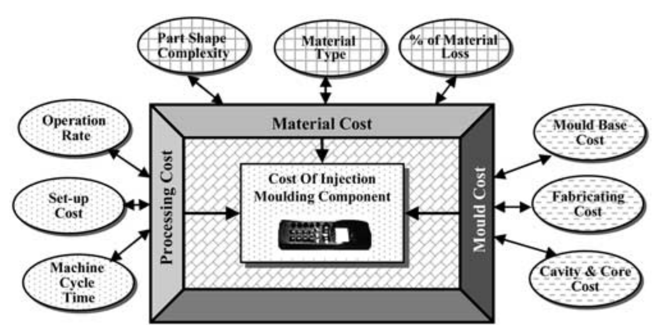

Fig. 10. The cost structure of the moulding component.

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. A sample of a decision table for hole making is given in Table 4.

Table 4. A sample of the 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

The set of rules from Table 4 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 unit time cost (R_i) multiplied by a corresponding machining time (T_i) as:

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

3.5 Costing Analysis Scenario

The scenario for machining component cost estimation is launched by specifying the production data, which enable the system to select the most economical assembly technique. The recommended assembly method is examined in the early stages of the design process. The user selects the manufacturing process (machining, injection-moulding, casting, sheet metal forming, and powder metallurgy) for the component. Currently, the system supports the first two processes, the rest are under development. The component model is constructed by the designer via the CAD system. The component envelope dimensions and volume are retrieved from the database in the CAD system. The system prompts the user to select between two options for the material. The first option is that the users specify the material and its properties, based on their own criteria. The second option is that the system executes 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 of each feature by applying the manufacturing process rules stored in the knowledge base.

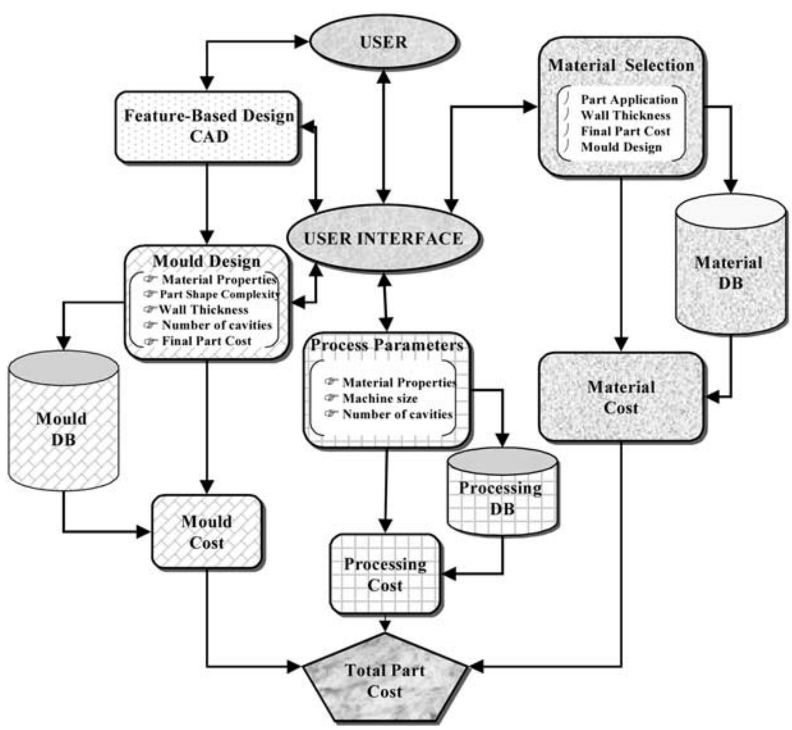

Fig. 11. The manufacturing cost framework of a moulded component.

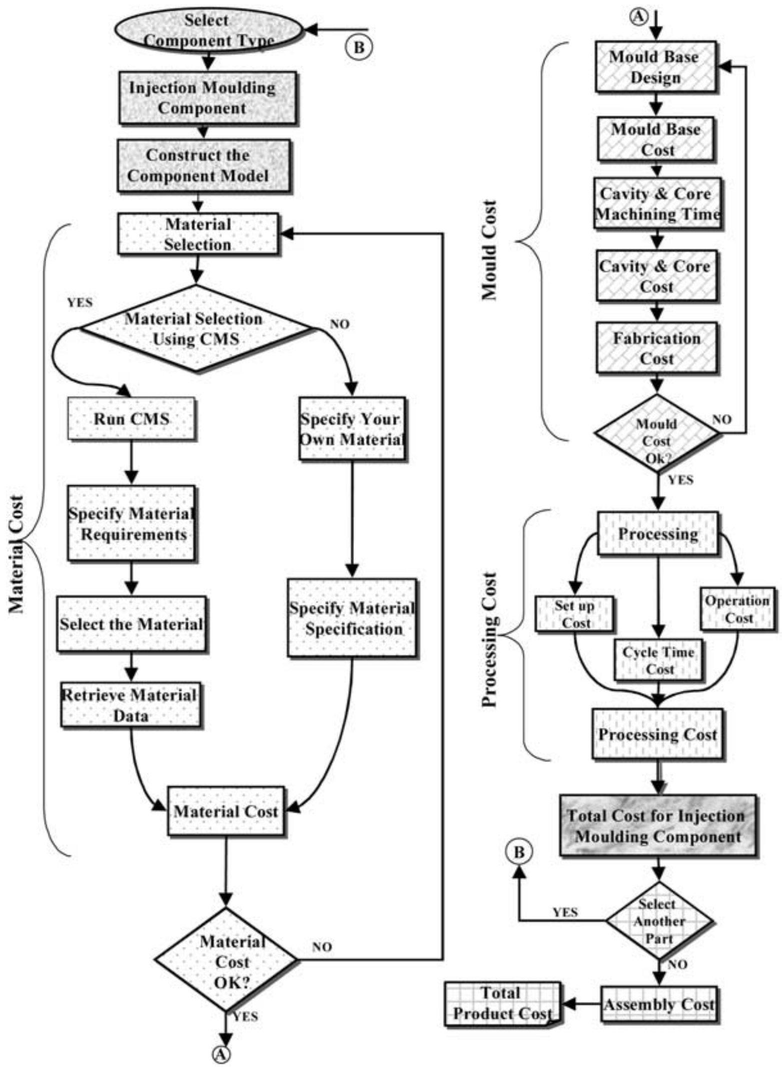

Fig. 12. The cost estimation model for an injection moulding component.

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 Fig. 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.

4. Cost Modelling of Injection Moulding Components

This section deals with estimating the manufacturing cost of injection-moulded components, which are used in a wide variety of industries, such as automotive, appliance, computer, communication and industrial equipment. 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 [24]. In conceptual design, a sketch or a conceptual model is configured based on the functional requirements of the product. 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 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.

A mould 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.

4.1 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. In this work, we focus 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 cost elements, namely, the mould cost, the material cost, and the processing cost (Fig. 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 mould 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.

The mould costs include mould base, mould manufacturing, and mould construction. 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 accounts for more than two-thirds of the total cycle time. Uniform cooling improves 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.

4.2 Manufacturing Cost Model for Moulded Components

The framework for the manufacturing cost of a moulded component consists of the material selection environment, the CAD system, the injection process environment, the user interface, and the mould design. This framework is shown in Fig. 11. The function of the CAD system is to support the feature-based part construction and modification function for the user to perform the design task. Material selection is an important 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, i.e. 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 the CMS on the candidate material. The material data is used to compute the material cost. 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: 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 allow thinner wall sections. On the other hand, thinner wall can inhibit component fillability. The mould cost depends mainly on the cost of the mould base and the costs of manufacturing the cavity and core.

The processing cost is obtained from the set-up cost, the machine rate, and the 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.

4.2.1 Material Cost

The main elements comprising 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 can be computed from the following form [14]:

$$C_{mt} = V_p \rho C_w \left(1 + \frac{f}{100} \right) \tag{7}$$

where,

C_{mt} = material cost, \$/component
V_p = component volume, m^3
ρ = material density, kg m^{-3}
C_w = unit price, \$ kg^{-1}
f = percentage of material loss

4.2.2 Mould Cost

The main constituents of mould costs are the cost of the mould base, the number of cavities, and the fabricating 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 dimension. These data are used to estimate the total cost of manufacturing a mould using the form [14]:

$$C_{mc} = C_{mb} + C_{c1} n^m + C_{oc} \tag{8}$$

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

4.2.3 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 Eq. (9) [14]:

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

where,

C_{pc} = processing cost per component, \$
T_{su} = set-up time, h
T_{cy} = machine cycle time, h
N_{bs} = batch size,
R_{op} = operation rate, \$/h
y = production yield (< 1)
n = number of cavities

The required machining cost of the moulded component can be computed from the Eq. (10) [14], that shows the three elements of moulded component cost:

$$C_{pp} = \frac{C_{mc}}{V_{ol}} + C_{mt} + C_{pc} \tag{10}$$

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

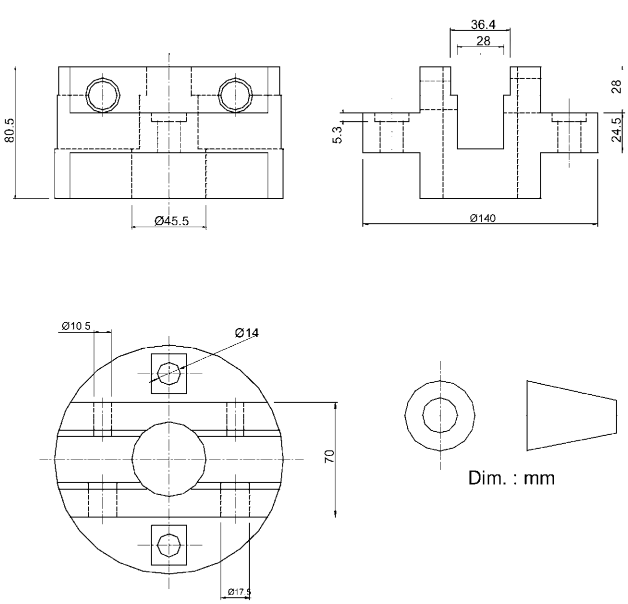

Fig. 13. A sample machined component.

4.5 Cost Analysis Scenario of Moulded Components

The system scenario for injection moulding product cost estimation is described next and is shown in Fig. 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 detail in Section 3.2. The material cost is estimated for the candidate material.

The system prompts the user to specify 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 the set-up cost, the operation cost and the machine cycle time. Based on the operation parameters such as number of operators per machine, number of working shifts, and annual operator cost, the operation cost is estimated. The processing cycle cost time usually includes of the machine opening and closing time, the injection or filling time, and the cooling time.

The same procedure is repeated for the remaining components. After estimating the cost of the product components, the system begins to estimate the assembly cost, based on the recommended assembly technique.

5. System Benefits and Implementation

There are several benefits gained as a result of implementing the proposed system. First, product manufacturing costs can be estimated during the early stages of the product development cycle. This enables designers/manufacturing planners to make more accurate estimates of the product cost at early stages of the design process. Secondly, it can be used to select the most economical 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. Thirdly, it will enable designers/manufacturing planners to reduce unnecessary downstream manufacturing costs, thus reducing the total product cost and product lead time.

Finally, the implementation of the system will generate a quicker response to customers' expectations.

The advent of the artificial intelligence systems has introduced a variety of knowledge representation schemes, such as frames, rules, logical terms, etc. An expert system Kappa-PC toolkit [22], AutoCAD as a CAD tool, Excel database, and CMS have been chosen to develop the proposed system. Kappa-PC supports frame-based object-oriented programming and high-performance rule-based reasoning. It also provides a programming environment and integrated set of tools to build knowledge-based systems for commercial and industrial applications. It allows applications to be written 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 a CAD tool is that

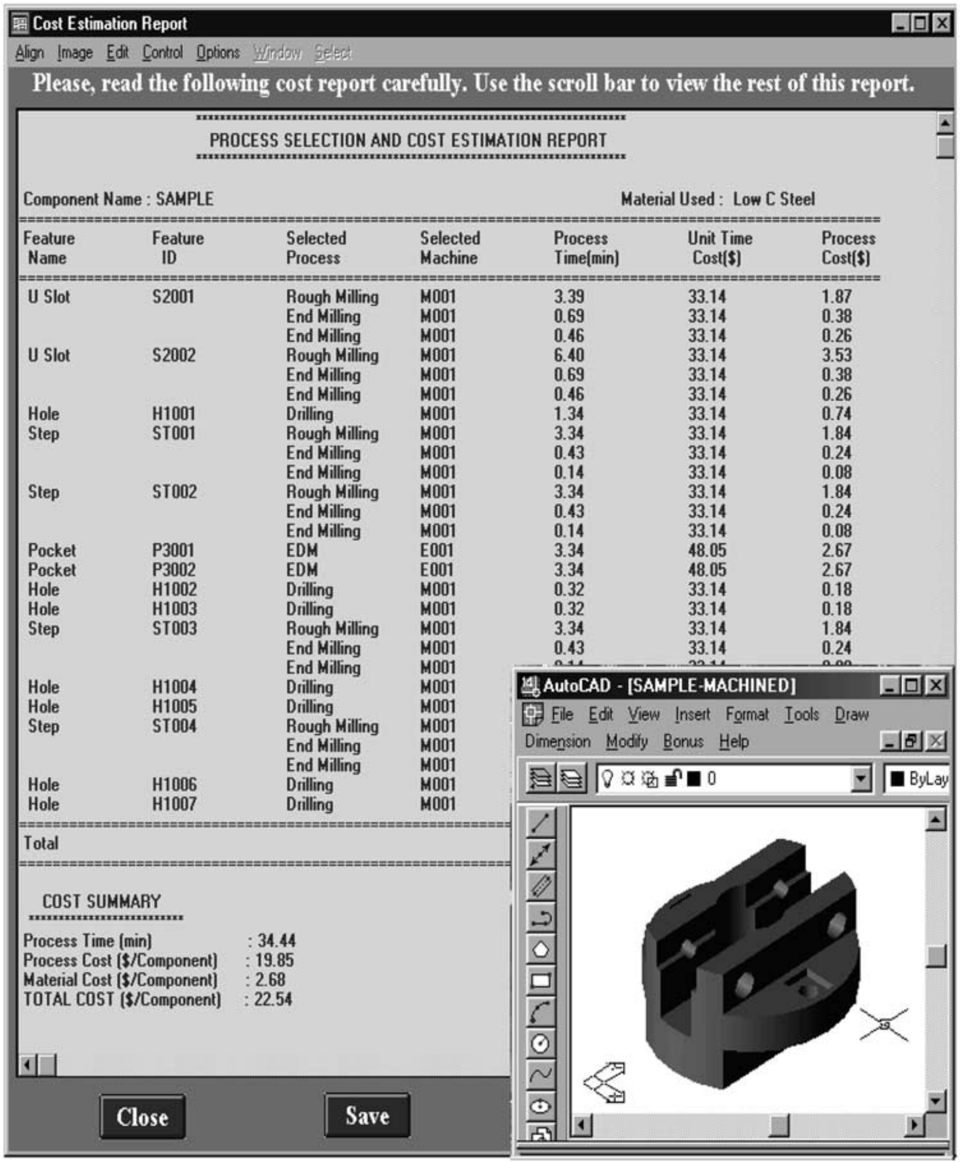

Fig. 14. The system window of the cost estimation report of the present case study.

it is widely used and has powerful interactive functions for editing graphics and drawings. The system runs on personal computers 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 evaluation procedures of the system will be outlined in the following section.

6. Case Study

6.1 Machined Component

In order to validate the system, a case study is used to demonstrate the capability of the system. Figure 13 shows a sample of a machined component with four different kinds of feature: two through slots, seven holes, four through steps and two pockets. 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. 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 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 computerised

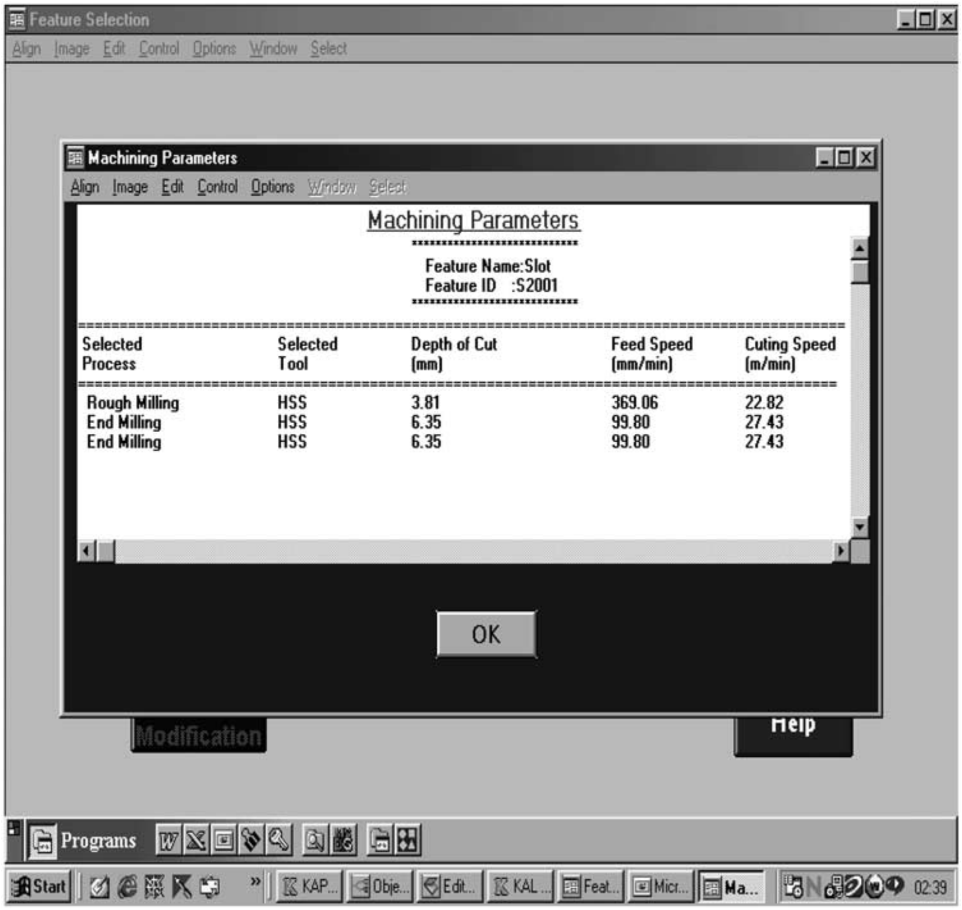

Fig. 15. The system recommendation for machining parameters of slot making.

numerically controlled (CNC) milling machine. The total cost rate (C_T) of this machine can be obtained from:

$$C_T = C_L + C_M \tag{11}$$

where,

C_L = labour cost rate ($ h^{-1})

C_M = machine cost rate ($ h^{-1}).

The labour cost rate is comprised of the direct labour wage rate and overhead. The machine cost rate consists of the machine depreciation rate and the machine overhead. The depreciation rate is calculated based on the working hours per year and amortisation period. The machine overhead includes the cost of routine maintenance, the cost of unexpected breakdowns and services, and the cost of factory space used.

The above two cost components are explained in the following:

1. Labour cost rate, C_L
   Annual labour cost
   Including overhead = $23 000
   Working hours per day = 8
   Working days per week = 5
   Working weeks per year = 48
   $$C_L = \frac{\text{AnnualLabourCost}}{\text{WorkingHoursPerYear}} = \frac{23\,000}{8 \times 5 \times 48} = 11.98 \text{ \$ h}^{-1}$$
2. Machine cost rate, C_M
   Equipment cost = $250 000
   Amortisation period = 8 years
   Overhead = 30%
   Working hours per year are the same as above.

C_M = Machine depreciation rate + Machine overhead =

$$\left[\frac{250\,000}{8 \times 8 \times 5 \times 48}\right] \times 1.3$$

$= 21.16$ \$ h^{-1}

Substituting the cost components into Eq. (11) gives:

$$C_T = 33.14 \text{ \$ h}^{-1}$$

The total machining cost rate of EDM is obtained from Yeo et al. [25].

Figure 14 illustrates the cost estimation report prepared by the system for the present case study. Feature-by-feature cost estimation that shows in the cost report is very useful for showing the user a specified feature with a high processing cost. Consequently, the user can adjust the design, based on the analysed results. The system recommendation for machining parameters for manufacturing a slot is illustrated in Fig. 15.

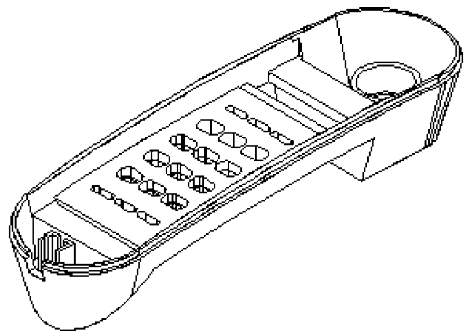

Fig. 16. Phone handset.

6.2 Injection Moulded Component

The system is used to estimate the cost of producing the phone handset shown in Fig. 16. The system allows the user to enter data relating to the product and production parameters. The data entered include the batch size, production volume, and component characteristics. The production parameters for the present case study are:

Batch size : 4000

Production volume : 90 000

The system has the capability to retrieve the envelope dimension and volume of the phone handset from the CAD system. The users can specify the material used, based on their own criteria or select the material from CMS software. The necessary material data is retrieved by the proposed system.

Figure 17 shows the retrieved data of the phone handset and the material used. 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 machine and the size of the mould base. Users can alter the default values to suite their own working conditions. The default information used in the present case study are shown below:

Mould default data

Number of base plates	3
Clearance between cavities (mm)	50
Clearance between cavity and plate edge	50

Default input data

Number of operators	1
Machine set-up time (h)	2
Annual labour cost ($)	23 000
Work hours per day	8
Work days per week	5
Work weeks per year	48
Number of shifts per day	3
Machine payback (years)	3.5
Production yield	0.9

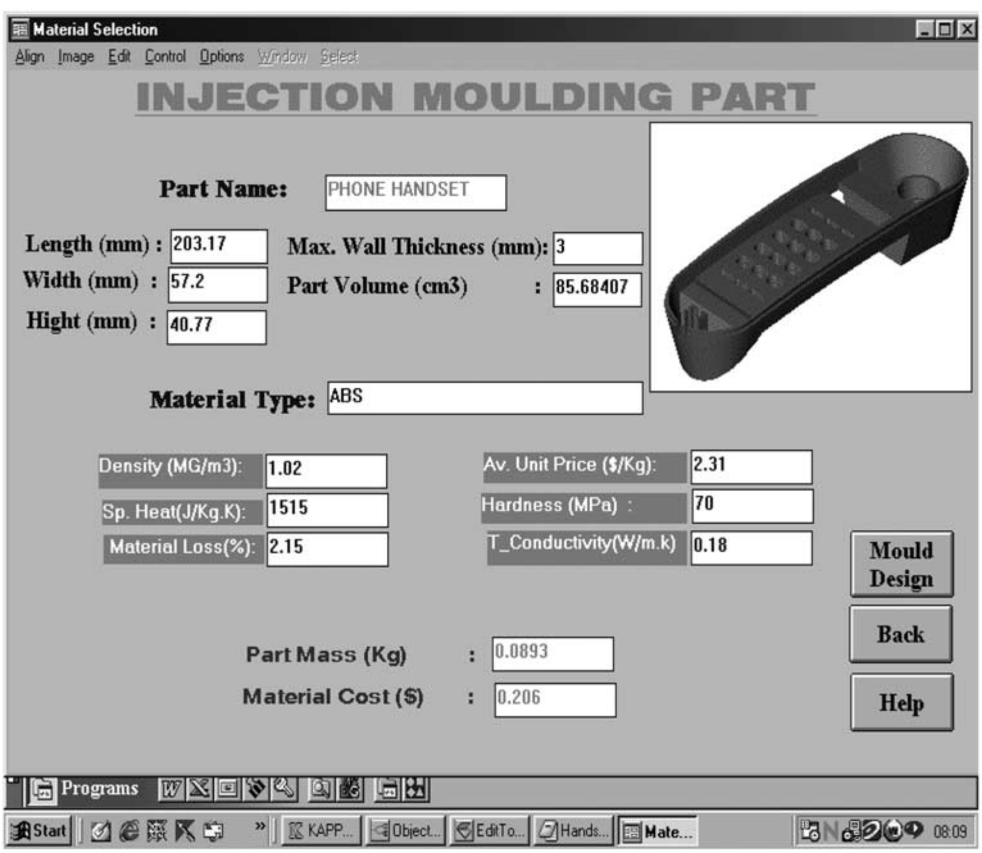

Fig. 17. Component parameters and material properties retrieved by the proposed system.

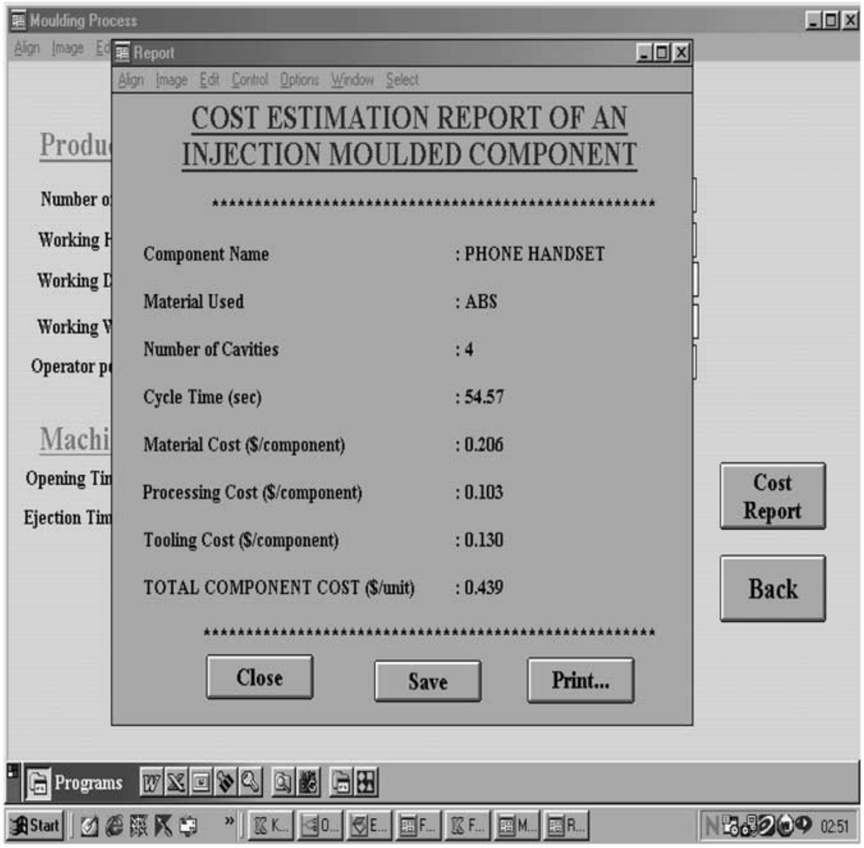

Fig. 18. The cost estimation report of the phone handset.

The output cost gives the cost of the material, the component processing cost, and the tooling cost, as shown in Fig. 18.

8. Conclusions

A methodology has been described for modelling product costs of machining and injection moulded products at the design stage of the product life cycle. An integrated knowledge-based system was used to implement this methodology. The proposed system consisted of two main modules, namely, cost modelling of a machining component and cost modelling of an injection moulding component. The framework for cost modelling of a machined component consisted of feature-based CAD system, material selection, process/machine selection, user interface, and cost-estimation techniques. The manufacturing cost model for a moulded component consists of material selection environment, CAD system, injection process environment, user interface, and mould design. The system can

1. Select a material as well as the manufacturing process based on a set of design and production parameters.
2. Estimate the total product cost, ranging from material cost to assembly cost.

The proposed system can be used in the early design stage so redesign cost and a long lead time are avoided. Hybrid knowledge representation techniques, such as production rules, frame and object oriented are employed to represent manufacturing knowledge in this work.

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

Fuzzy logic-based knowledge representation is applied to deal with uncertainty in the knowledge of cost model. 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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