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Manufacturing cost modelling for concurrent product development

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Abstract

This research work aims to develop an intelligent knowledge-based system that accomplishes an environment to assist inexperienced users to estimate the manufacturing cost modelling of a product at the conceptual design stage of the product life cycle. Therefore, a quicker response to customers' expectations is generated. This paper discusses the development process of the proposed system for cost modelling of machining processes. It embodies a CAD solid modelling system, user interface, material selection, process/machine selection, and cost estimation techniques. The main function of the system, besides estimating the product cost, is to generate initial process planning includes generation and selection of machining processes, their sequence and their machining parameters. Therefore, the developed system differs from conventional product cost estimating systems, in that it is structured to support concurrent engineering. Manufacturing knowledge is represented by hybrid knowledge representation techniques, such as production rules, frames and object oriented. To handle the uncertainty in cost estimation model that cannot be addressed by traditional analytical methods, a fuzzy logic-based knowledge representation is implemented in the developed system. Based on the analysis of product life cycle, the estimated cost included material, processing, machine set-up and non-productive costs. A case study is discussed and demonstrated to validate the proposed system.

Keywords: Feature-based design; Concurrent engineering; Manufacturing cost modelling; Object-oriented programming; Process optimisation; Fuzzy logic

1. Introduction

The current trend forces companies to produce low-cost and high-quality products in order to maintain their competitiveness at the highest possible level. There is no doubt that, reducing the cost of a product at the design stage is more effective than at the manufacturing stage. Therefore, if the product manufacturing cost can be estimated during the early design stage, designers can modify a design to achieve proper performance as well as a reasonable cost at this stage and encourage designers to design to cost.

Past studies 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 to cost is a necessary step towards optimising product costs. Fig. 1 illustrates the percentage of product costs set and incurred in different phases.

Cost can be employed as an evaluation criterion in design in two ways. It can be used either in a design-to-cost or design-for-cost context. Design-for-cost is the conscious use of engineering process technology to reduce life cycle cost while design-to-cost provides a design satisfying the functional requirements for a given cost target.

2. Literature review

Cost estimation is concerned with the predication of costs related to a set of activities before they have actually been executed. Cost-estimating approaches can be broadly classified as intuitive method, parametric techniques, variant-based models, and generative cost estimating models. However, the most accurate cost estimates are made using the generative 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.

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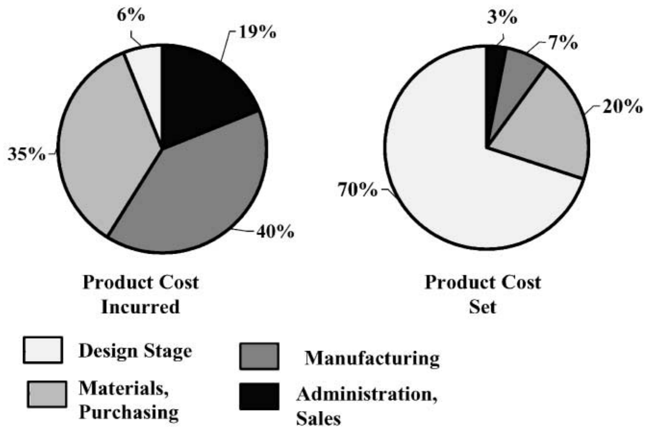

Fig. 1. Product costs set and incurred in different phases [2].

Abdalla and Knight [2] 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.

A framework to estimate the lowest product manufacturing cost from its AND/OR tree representation of an alternate process was developed by Wei and Egbelu [3]. 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.

Venkatachalam et al. [4] developed an object- and rule-based expert system for process selection and cost estimation for cast and forged products. Luong and Spedding [5] 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 integrated system, which caters for the requirements of small to medium-sized companies, involved in batch production. Luong and Spedding's system is lacking an interface to a CAD system, and capability of process plans optimisation.

Allen and Swift [6] 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.

French [7] addressed the problems of modelling cost in terms of function. The uses of function costing include the estimation of cost directly from the specification, the comparison of alternatives, and the detection of areas of potential cost reduction.

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. In their paper, the major factors used to estimate the machining time of a feature were type, process planning information, geometrical data and surface finish requirements. The proposed framework of Ou-Yang and Lin has taken into consideration only conventional machining process. However, machining processes can have limitations in producing certain manufacturing features. For example, the machining process is often not suitable for producing a feature with very small dimensions or very high surface finish requirements. Ou-Yang and Lin's model is suitable for generating manufacturing costs of prismatic components. Gayretli and Abdalla [9] 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.

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 [10]. 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. [11]. The models presented in this work were on medium-to-light mass mild steel parts, i.e. parts up to 40 kg and assemblies up to 200 kg.

Accurate cost data is a critical factor for successfully implementing cost estimation system. Sheldon et al. [12] 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 provided by a cost accounting system, to establish the appropriate cost structures suitable for different groups of DFC users.

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 change-over and set-up time were the most significant components of machining time, which implied that the shorter the change-over and the set-up time, the lower the machining cost. Also, the smaller the number of operations, the lower the machining cost was. Operation-based cost models were one of the earliest attempts in estimating manufacturing costs. Due to the type of information required, these models could be used effectively only in the final design stage.

Shehab and Abdalla [14] developed an intelligent knowledge base system for product cost modelling at early design stage. 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.

Injection moulding process is a process that gives high production rates, excellent quality and accuracy of products, and low manufacturing cost. Therefore, a number of cost model systems were developed for estimating the manufacturing cost of injection moulding components [15–17].

The cost involved in performing assembly operations for product assemblies is often significant, and hence must be included in the manufacturing cost estimation. Past studies have shown that the proportion of assembly cost could be as high as 50% of the total manufacturing cost [4] in the case of many mechanical and electrical assemblies. Assembly cost estimation was one of the criteria used to determine the most economical assembly technique for a product [18].

Fuzzy logic has been used as the basis for controlling industrial processes and consumer products. El-Baradie [19] developed a fuzzy logic model for machining data selection. The model is based on the relationship between the hardness of a given material and the recommended cutting speed. A fuzzy logic expert system for estimating excavation cost was developed by Mason and Kahn [20].

The above literature review shows that a number of cost models have been developed for various kinds of applications. But little effort was made in cost modelling at an early stage of the entire product development cycle. They lacked the material selection capability. They have not considered non-productive times such as, set-up, loading and unloading, and tool changing times. 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 framework PC-based system for product cost modelling is developed. The development process has been through two major steps: firstly, constructing a knowledge-based system (KBS) for cost modelling. Secondly, integrating the KBS with both material selection database and a CAD system has been implemented.

3. The developed system model

To obtain an appropriate estimation of 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 of cutting tool type and cutting conditions (e.g. feed rate 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 proposed model for cost modelling of machining processes embodies a CAD solid modelling system, user interface, material selection, process/machine selection, and cost estimation techniques. The architecture of the cost modelling system of a machining product is shown in Fig. 2.

Detailed descriptions of each component in the proposed framework are set out in the following sections.

3.1. Material selection and costing

Material selection is an important stage and complicated one 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 the user select to specify the material based on his own criteria. The second one is that the system executes Cambridge Material Selection (CMS) software [21]. CMS is a computer package consisting of a database, a management system, and a graphical user interface. The database contains quantitative and qualitative data for a wide range of engineering material: metals, polymers, ceramics, composites and natural materials. The management system provides an interactive graphical selection environment suitable for mechanical engineering design. With CMS, the most appropriate material will be determined based on previous input of product concepts and requirements.

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 the following equation:

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

where V is the raw material component volume, m^3, ρ the material density, kg/m^3, and C_w the unit price, $/kg.

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

3.2. Process/machine selection

The process/machine selection module consists of a feature specification file, knowledge base of the feature manufacturing process, machine specification database, machinability database, and feature machining time function (see Fig. 2). The feature specification file is used to save data on the individual features of a component such as the volume and the defined parameters. The parameter type is varied according to the different kinds of feature. The feature manufacturing knowledge base contains the manufacturing processes required to

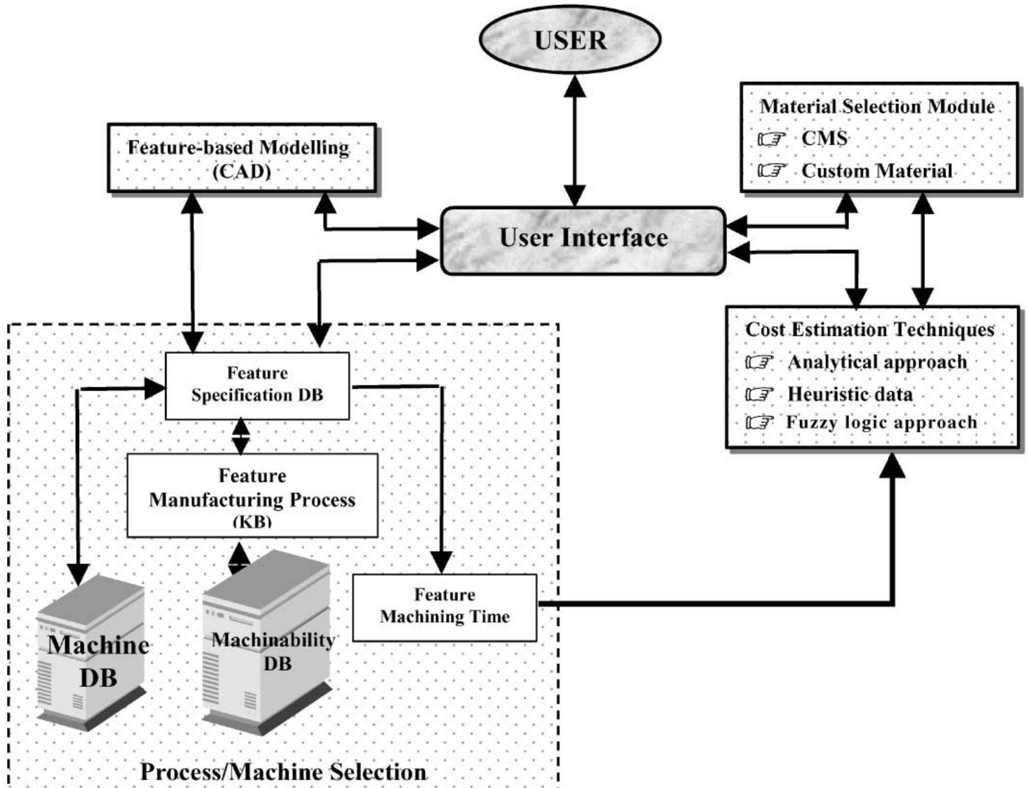

Fig. 2. The architecture of cost estimation model for machining processes paradigm.

produce certain features with different surface finish and tolerance.

The machine specification database stores related data on the available machines and the kind of operations, that can be performed by each machine, the surface finish and tolerance ranges for individual machines, and the operating cost for each machine. The machinability database contains information on machinability of the work material, Brinell hardness, recommended cutting speed and feed rate. The machine data and machinability are obtained from machining data handbooks (e.g. [22]). Table 1 shows a sample of machinability database for rough milling operation.

The selection and optimisation of machining parameters are carried out through a series of interaction between various modules including feature specification database, feature manufacturing process knowledge base, machine database, and machinability database.

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.

3.2.1. Feature representation

A feature is defined as a generic shape carrying product information, which may be aid design, or communication between manufacturing and design, or between other engineering tasks such as assembly, manufacturing, and maintenance. Features should be represent explicitly in a form that matches manufacturing knowledge. To generate a process plan, it is necessary to analyse the form features directly related to manufacturing under consideration. In this analysis, manufacturing form features are the key for the generation of the machining processes and estimation of manufacturing costs. The use of manufacturing form features helps designers to simplify process planning without consideration of component manufacture. Therefore, the feature-based representation technique has been used to represent the component and its features in a greater detail. Cost-effective process planning can be achieved by the definition of manufacturing form features that are derived from topological and geometrical description of the component. For instance, a slot is form feature defined by its parameters such as its identification number (ID), name, length, width, height, locations, tolerance, and surface finish. These parameters are used to select the machining processes, set-up, fixtures, cutting tools and cutting parameters can be chosen. Consequently, the machining time and cost can be estimated.

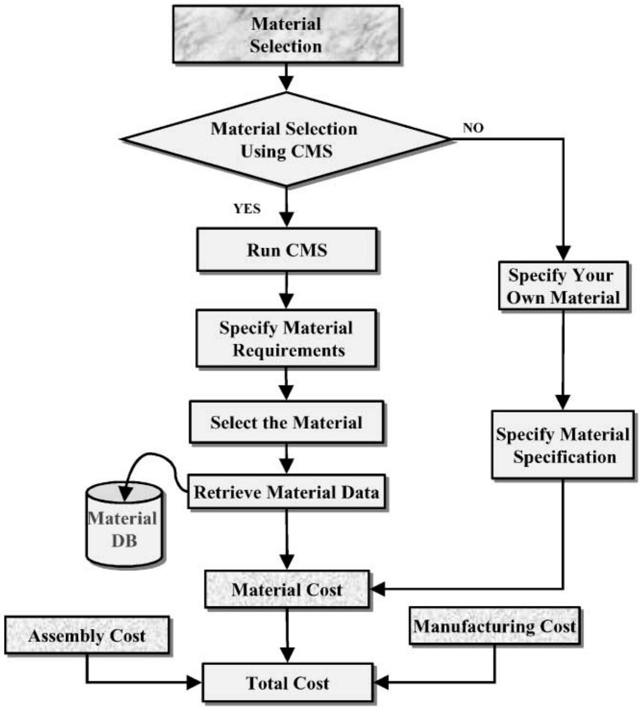

Fig. 3. Material selection module.

The proposed model contains knowledge about form features and their manufacturing process. Manufacturing form features are represented by using an object-oriented representation technique. The feature parameters are then passed to the feature specification database.

3.2.2. Approaches to knowledge representation

Many representation techniques, such as production rules, object orientation, case base and framework have been reported in artificial intelligence (AI), to meet the requirements for specific problems.

Manufacturing knowledge is represented by hybrid knowledge representation techniques in this research. These techniques, such as production rules, frames and object orientations are described in detail as follows.

3.2.2.1. 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. 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 expert system toolkit [23], developed by Intellicorp, 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.

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

Pocket_Making Rule1:
If
(The Feature is a pocket) and
(The pocket corner is sharp) and
(The surface finish $< 6.35\ \mu m$) and
(Additional rules)
Then
(E001 is selected)

Table 1
A sample of machinability database

MaterialName	MaterialID	Hardness (Bhn)	DepthOfCut (mm)	CuttingSpeed (m/min)	Feed/Tooth (mm)
Grey cast iron	MFECGG_$$$	120	3.8	56.39	0.406
(BS grades 100–400)		320	0.64	15.24	0.127
Steel, low carbon	MFECSLC$$$	100	6.35	25.91	0.127
		150	1.27	30.48	0.178
Steel, medium carbon	MFECSMC$$$	125	6.35	22.86	0.127
		175	1.27	27.86	0.178
Aluminium alloys (wrought)	MALW_$$$	30	6.35	304.80	0.559
		150	0.64	274.32	0.254

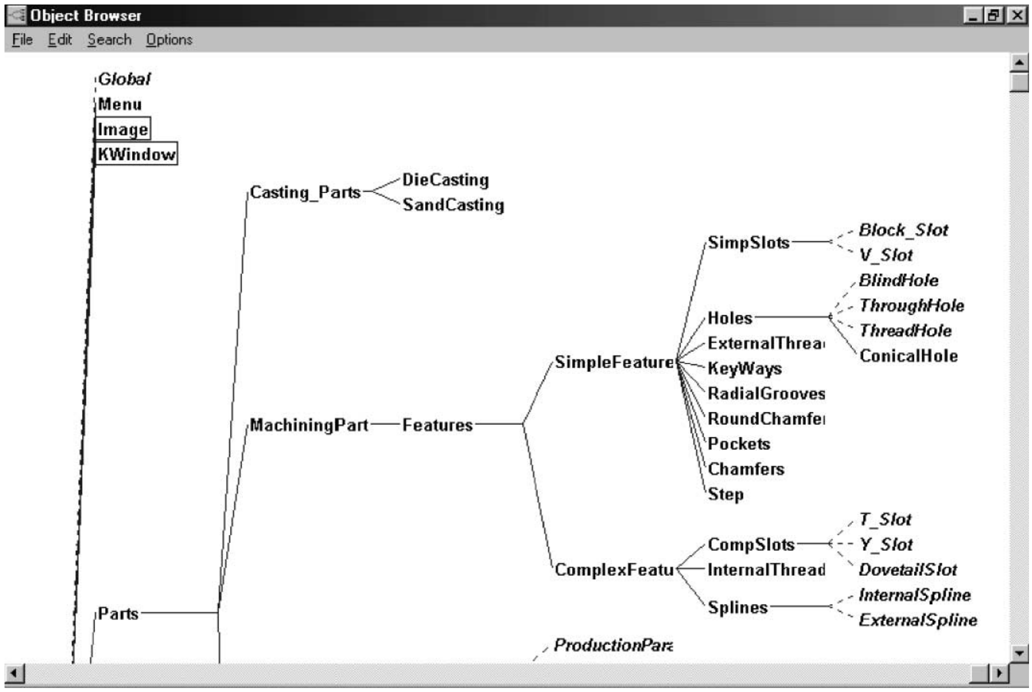

Fig. 4. Object-oriented representation of machining features.

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

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 CNC 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)

3.2.2.3. Object-oriented knowledge representation. This approach provides a very effective and efficient way for organising design, manufacturing, and costing objects, such as machine tools, cutting tools, features, and material properties into various classes. The classes are represented in hierarchies. Fig. 4 shows object-oriented representation of some machining features. A class is made up of a class name and several subclasses, consisting of a number of objects with a number of slots, attributes such as feed rate, tolerance, and surface finish. All classes can be broken down into subdivisions until all components of the class are determined. Data abstraction, inheritance, and modularity are the most powerful characteristics of object-oriented technique. Inheritance enables the designer to define a specific value into a higher class each can be inherited by the lowest class of the hierarchy.

3.3. User interface module

An interactive user-friendly interface has been developed to allow users to customise the system easily and efficiently. The Kappa-PC toolkit features were implemented to create the user interface. Menus, popup windows, and sessions are extensively used to get user defined values in this research. The user interface enables users to interact with a CAD system (AutoCAD) to create 3-D solid models, as well as with the Cambridge Material Selection (CMS) software. The retrieved component envelope dimensions, geometric volume and the material properties are displayed in an efficient way. The user communicates with the system by a mouse, a keyboard, and a super panel including menu and active images. The various elements of the product cost are reported to the user in a Kappa-PC window. Finally, the user is provided with options to clear the working memory and restart another application, make hard copy of the system recommendations and reports, or quit the system altogether.

3.4. Cost estimation techniques

When the heuristics data is not available, algorithmic or fuzzy logic techniques will be used. Therefore, the developed system allows users to generate accurate cost estimates for new designs and explore alternative materials and process.

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].

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} is the time required to accomplish the machining operation j of feature i, k_j the coefficient for the operation j, and p_{ijk} the value of a parameter or the reciprocal of a parameter used in defining feature i.
2. Computation of the required machining cost for each operation:

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

   where C_{ij} is the estimated machining cost for the operation j of feature i, M_h the unit time cost (\$/min) for machining h (machine h is selected to perform operation j), and S_h the 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 is the estimated machining cost for each feature i.
4. Computation of the required machining cost for each component:

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

   where TC is the estimated machining cost for the component.

The machining operations times are usually divided into set up times and run times. Run time is the time required to complete each part. The total manufacturing cost is computed by adding the machining cost, material cost, set up and non-productive costs.

3.4.1.1. Set-up costs. 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 the manufacture of one or more identical or similar parts.

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 [22].

3.4.1.2. Non-productive costs. Non-productive costs are incurred every time the workpiece is loaded into (and subsequently unloaded from) a machine tool. The non-productive costs would be quite small, if one machining operation and one pass are used to produce a part. 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.

3.4.2. Fuzzy logic approach

By applying fuzzy logic approach to cost estimating, it is possible to handle the uncertainty in cost estimation problems that cannot be addressed by the traditional techniques. A fuzzy production rule is similar to the traditional type of production rules except that the conditions in the production rules are replaced with linguistic expressions to which truth-values are assigned. The difference between a fuzzy expert system and the traditional expert system is that the reasoning process used to reach conclusions is different. 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. No attempts have been made to estimate the cost for complex feature that has more than two cost drivers. To deal with

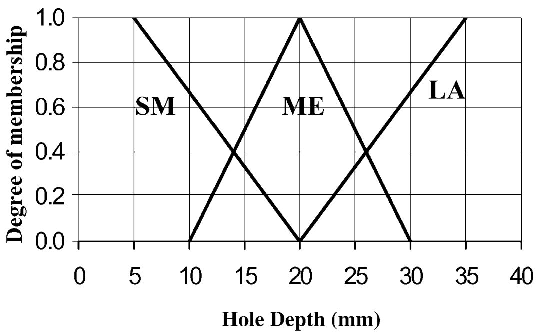

Fig. 5. Membership function for hole depth.

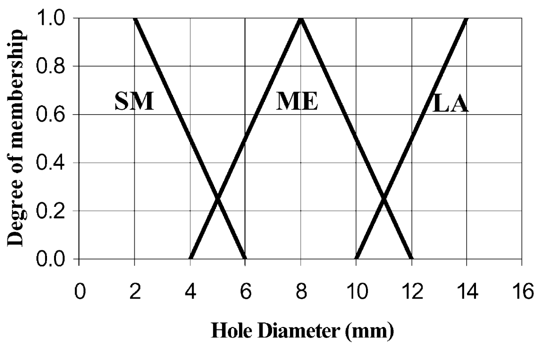

Fig. 6. Membership function for hole diameter.

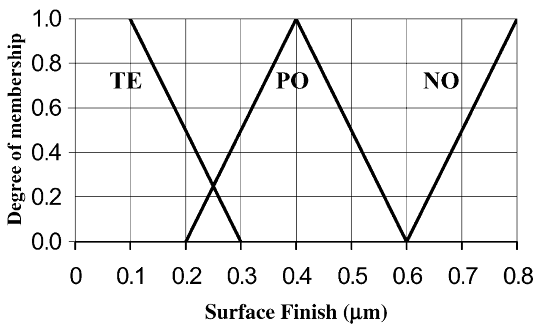

Fig. 7. Membership function for surface finish.

uncertain knowledge on cost estimation, a fuzzy technique is applied in this system. For this fuzzy technique, with three input variables each of which consists of three membership functions, a $(3 \times 3 \times 3)$ decision table with 27 rules are constructed. An example of a fuzzy logic system capable of estimating the machining time of a drilling hole is presented, in order to explain the steps in developing a fuzzy model. The input cost drivers are hole diameter, hole depth, and surface finish. While the output variable is the machining time. Figs. 5–8 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) (Figs. 5 and 6). Membership functions for surface finish are texture (TE),

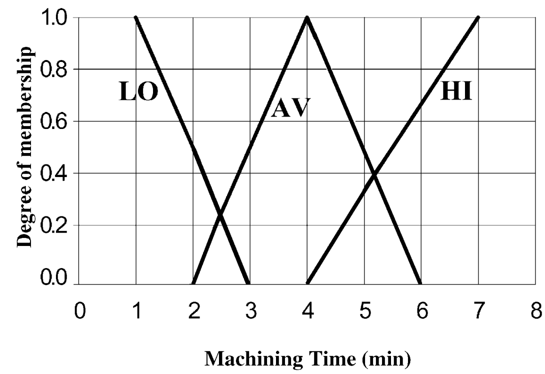

Fig. 8. Membership function for machining time.

Table 2
A sample of the decision table for hole making

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

polish (PO), and normal (NO). Membership functions for machining time are low (LO), average (AV), and high (HI).

Decision tables, that provide a means for system rules, can be used to indicate the relationships between the input and output variables of the fuzzy logic system. A sample of a decision table for hole making is illustrated in Table 2.

The set of rules from the above decision table is:

Hole_Rule1:
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)

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 small) and
(The hole diameter is small) and
(The required surface finish is texture)
Then
(The machining time is average)

The machining cost (C_m) of any feature is equal unit time cost (R_i) multiplied by a corresponding machining time (T_i) as

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

3.5. System scenario

Product cost estimation scenario is started 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 to consider it during the component design. 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 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 currently under development. 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 Cambridge Material Selection (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 include the feature geometry, surface roughness, and tolerance. 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.

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 process 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 proposed cost analysis scenario 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. System implementation and benefits

The prototype system is developed with the attributes of well-engineered software system, such as maintainability, reliability, and efficiently [24] in mind. The system is designed to provide the users with option of either running the entire integrated system or operating the individual modules separately.

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 developed by Intellicorp, 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 system for commercial and industrial applications. It allows writing applications in a high level graphical environment and generates standard ANSI C code and GUI runtime. The rules of Kappa-PC have been implemented for process selection and cost estimation heuristics. The reason to select AutoCAD as CAD tool is that it is widely used and has powerful interactive functions in editing graphics and drawings.

The system runs on personal computers (PC) and is designed to minimise the number of manual keyboard inputs wherever possible, as it is menu driven. Relational databases are used to produce a generic cost estimation system.

The tangible benefit of implementing this system is that the product manufacturing cost can be estimated at the early stage of the product development cycle. Therefore, a quicker response to customers' expectations is generated. 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 unnecessarily downstream manufacturing costs thus reducing total product cost and product lead-time. The provision of manufacturing costs at the design phase provides an important communication link between the design activity and downstream manufacturing activity. The evaluation procedures of the system will be outlined in the following section.

5. Application of the proposed system

A case study is used to demonstrate the capability of this system. A sample of machining component (Socket) was subjected to analysis its design in order to estimate the manufacturing cost by the proposed system. The

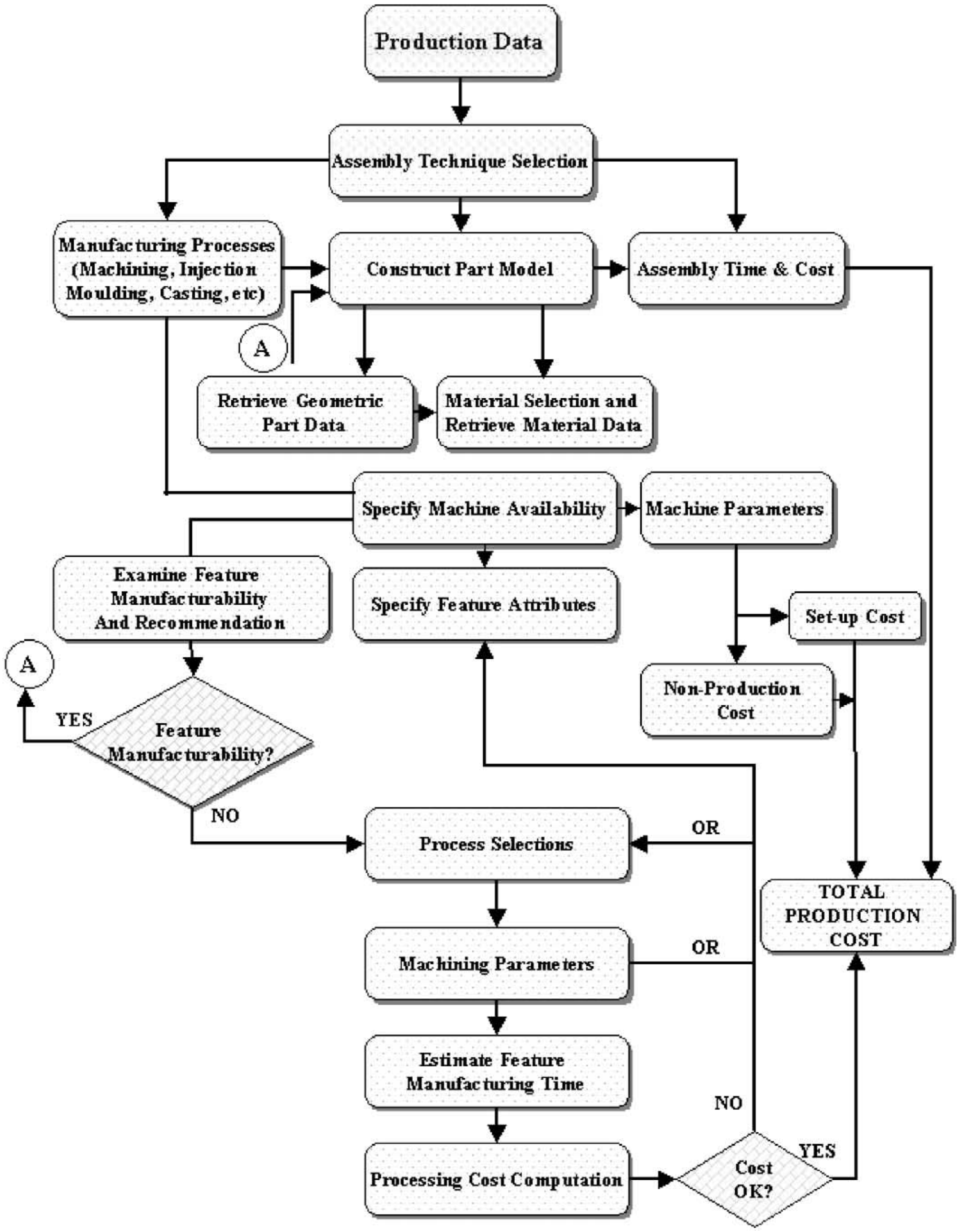

Fig. 9. The system scenario of the developed cost analysis process.

machining component has four different kinds of features as shown in Fig. 10: two through slot, seven holes, four through steps and two pockets with sharp corners. 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 material cost is estimated based on 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 computerised numerically controlled (CNC) milling machine. The total cost rate (C_T) of this machine can be obtained from the following equation [14]

$$C_T = C_L + C_M, \tag{7}$$

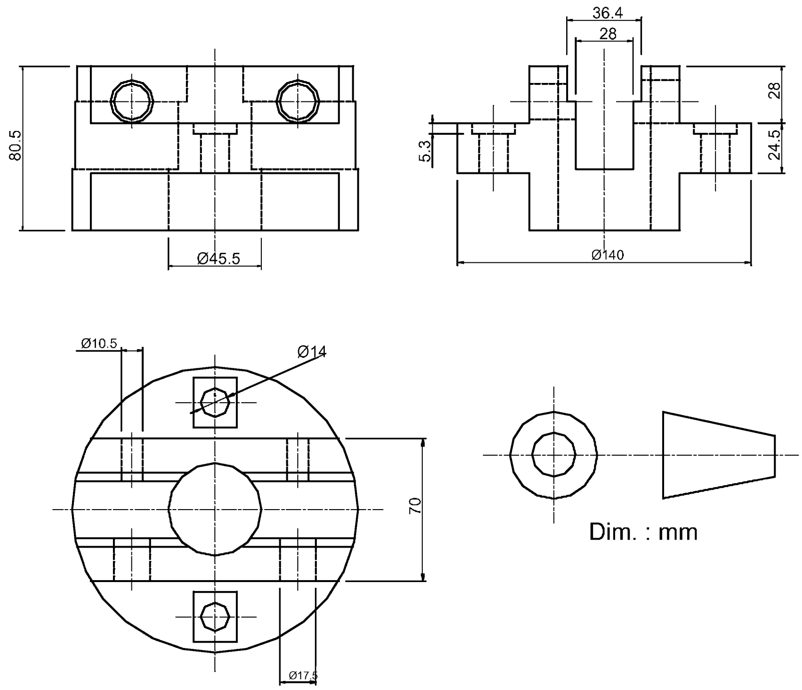

Fig. 10. A sample-machined component (socket).

where C_L is the labour cost rate (\$/h), and C_M the machine cost rate (\$/h).

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.

Labour cost rate (C_L) can be estimated as follows:

$$C_L = \frac{\text{AnnualLabourCostIncludingOverhead}}{\text{WorkingHoursPerYear}}.$$

Machine cost rate, C_M is calculated as follows:

$$\text{CM} = \text{Machinedepreciationrate} + \text{Machineoverhead}$$

$$= \left[\frac{\text{MachineCost}}{\text{WorkingHoursPerYear}}\right] \times (1 + \text{Overhead}).$$

By substituting the cost components into Eq. (7), C_T can be calculated.

The system displays the default parameters of production and machine parameters and based on the user's response, estimates the unit time cost, non-production time and set up time accordingly. The production parameters include total annual labour cost and working hours per year. While the machining parameters consist of machine cost, machine overheads, and amortisation period.

Fig. 11 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 the user to indicate a specified feature with high processing cost. Consequently, the user can adjust the design based on the analysed results. The system found that, the two pockets with straight corners require to be machined by electrical discharge machine (EDM). The total machining cost rate of EDM is obtained from Yeo et al. [25].

6. Conclusions

An intelligent prototype system for modelling product costs at the conceptual design stage of the product life cycle has been demonstrated in this research paper. The proposed system is composed of a CAD (computer aided design) solid modelling system, user interface, various knowledge bases, process optimisation, databases, and cost estimation technique module. The system is integrated with a CAD system and material selection software, to facilitate the product representation and the material selection processes.

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

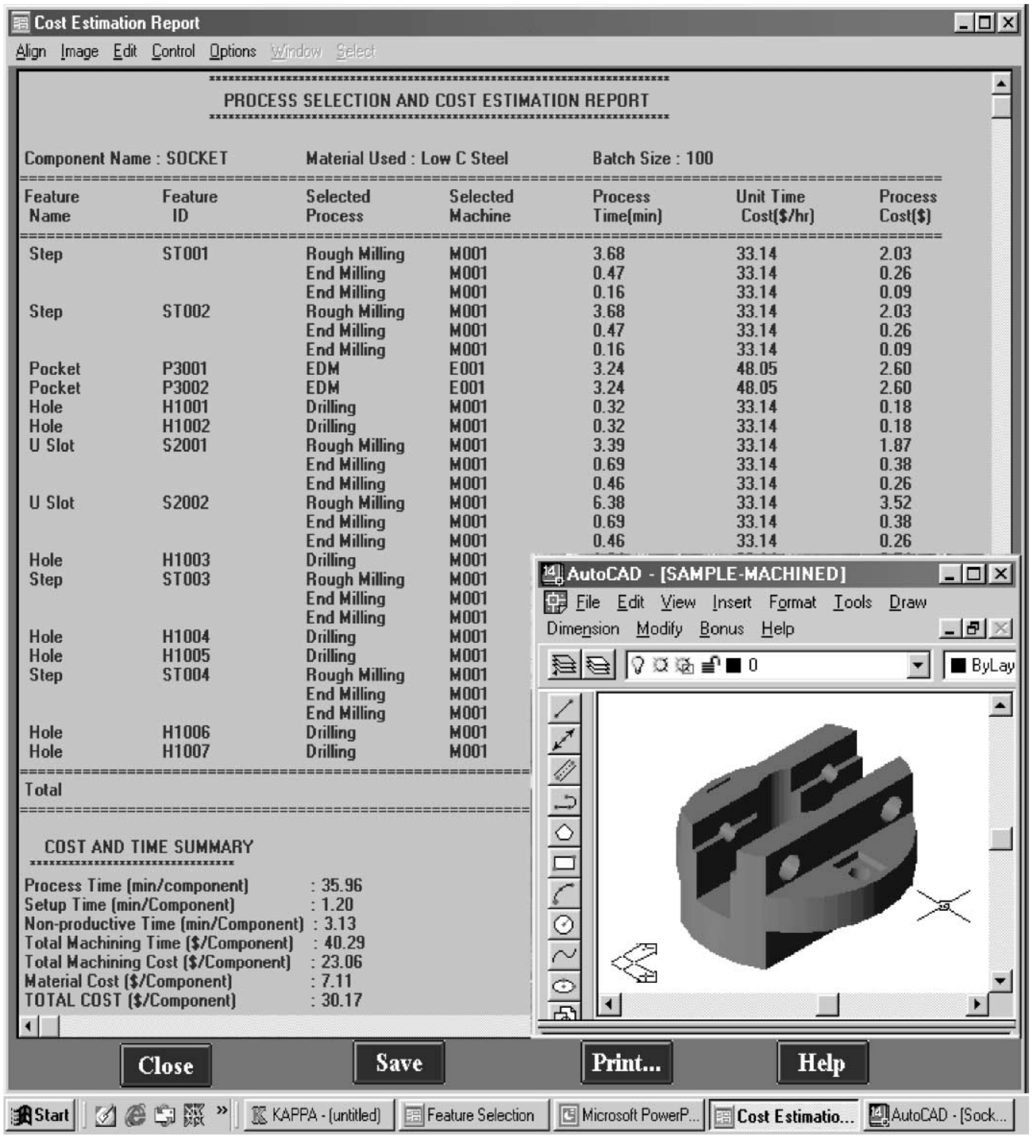

Fig. 11. The system window of the cost estimation report of the present case study.

representation techniques, such as production rules, frame and object oriented are employed to represent manufacturing knowledge in this research. Fuzzy logic-based knowledge representation is applied to deal with uncertainty in the knowledge of cost model.

The system has the capability: (1) to recommend the most economical assembly technique, (2) to select a material as well as the manufacturing process based on a set of design and production parameters, and (3) to estimate the total product cost, ranging from material cost to assembly cost. The proposed system has been validated through a case study. This work is part of an on-going research programme aims to develop a comprehensive system that can be used to estimate the product cost of all the manufacturing processes, such as sheet metal and casting processes.

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