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Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation

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The major objective of concurrent engineering is to consider the related downstream manufacturing during the design stage. Estimating manufacturing cost during the early design stage is one area that has been given little attention by researchers. However, if the product manufacturing cost can be estimated during the design stage, designers can modify a design to achieve proper performance as well as a reasonable cost at an early stage of the product development process.

Basically, manufacturing cost is determined by shape complexity, product precision and tooling process. That is, if these data can be obtained and considered during the design stage, estimating manufacturing cost during the early product development stage will become a feasible task.

In this research, a framework for estimating the manufacturing cost in terms of a feature-based approach is proposed. This system tends to estimate the manufacturing cost of a design according to the shapes and precision of its features. The objective of this research is to provide a tool to assist a designer, who has little knowledge about the manufacturing process, to estimate the fabrication cost of a design during its conceptual stage, in order to reduce unnecessary costs in the downstream process.

Keywords: Cost estimation; Feature based; Framework; Integrated; Manufacturing

1. Introduction

The major concept of concurrent engineering (CE) is to put the majority of effort in the product design stage to analyse the factors which might affect subsequent production processes, and hence save overall product development time. Several DFX methods such as design for manufacturing (DFM) [1] or design for assembly (DFA) [2,3] have been developed to implement the ideas of CE. A few researchers have applied feature-based and/or knowledge-based approaches to achieve DFA and DFM concepts [4,5].

The development of CAD/CAM systems is also playing a key role in implementing DFX concepts. The recently developed parametric and feature-based approach has improved the process of integrating CAD/CAM systems with DFX methods. A part model is constructed in terms of form features defined by a group of parameters. The information about form features and parameters can be used by an analysing scheme such as a knowledge-based system for downstream processes evaluation.

Among those DFX methods, DFC (design for cost) is one area which has been considered by many researchers recently. The basic concept of DFS is to estimate the manufacturing cost during the early design stage in order to achieve the following objectives:

1. To find the segment of a part model which might cause a high manufacturing cost.
2. To provide an environment to estimate alternative cost for comparative design models.

In this paper, an approach is proposed, which integrates a feature-based CAD model and a database storing product and process cost. This approach will analyse a part model designed in a feature-based CAD system according to certain criteria in order to roughly estimate its required machining cost. Analysing the results can be used to achieve the above two objectives.

2. Background

Increasing productivity is one of the major concerns in production engineering. Proper cost estimation is necessary to ensure maximum productivity. According to the Society of Cost Estimating and Analysis (SCEA), cost estimating can be defined as "the art of approximating the probable worth or cost of an activity based on information available at the time" [6]. In addition, the difference between an estimated cost and an actual cost is that only the most important factors are considered in an estimation process. Some minor elements or factors which cannot be predicted are not given attention during the estimation [7]. Based on the above description, cost

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estimation predicts the cost based on available information. The estimated cost might be near to the actual cost but might have certain deviations from it. However, the estimated result can provide guidance for the planner or designer to justify his/her approach.

In the traditional product developmental cycle, such as for an injection moulded product, the cost analysis is usually performed at the end of the process. The required cost is estimated after the stages of defining part specifications, selecting material and process, designing the part model and constructing the mould [8]. In this process, if the estimated cost exceeds the expectation, it might be too late to modify the design in order to reduce the total cost. Although modern software technologies such as CAD, CAM and CAE have been applied in several product developmental processes, it seems that the developmental precedence is seldom changed (Fig. 1(*a*)).

In a modified product developmental cycle, the cost estimation is performed before the mould design stage. Basically, in this process, the cost evaluation task is based on certain simplified data such as the approximate volume of the part, the overall tolerance of the design, and the selected material. Although certain computer tools also can be used in this cycle (Fig 1(*b*)), it still requires an experienced person to read and interpret the design during the cost estimation stage.

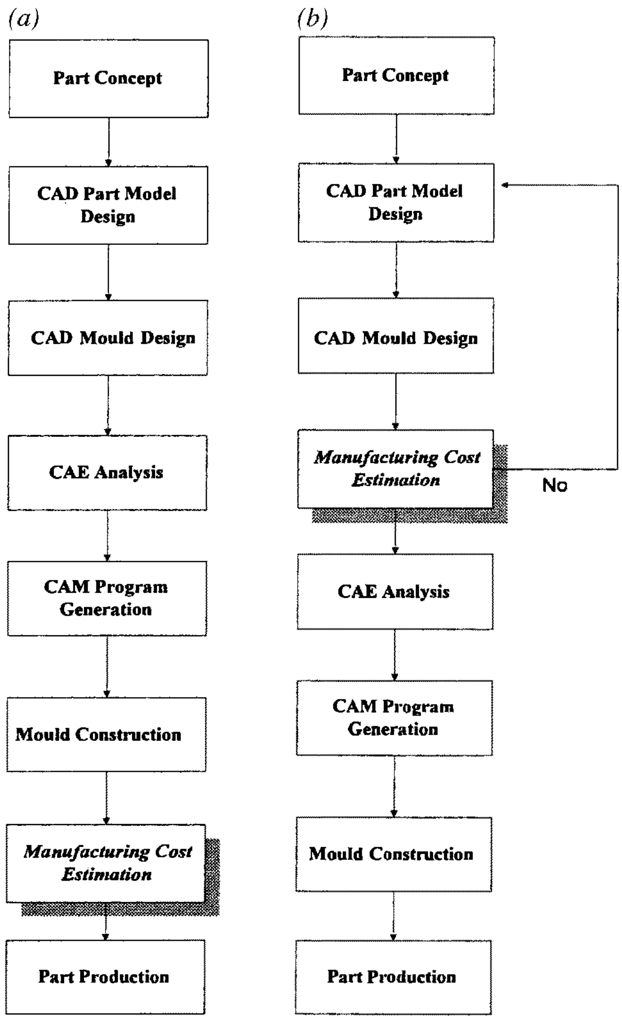

Fig. 1. (*a*) Traditional product development process. (*b*) Modified product development process.

Research results show that over 70% of the production cost of a product is determined during the conceptual design stage [9–11]. In other words, the majority of the production cost is determined by a designer who might have little knowledge about the cost of manufacture. Since a design modification requires only a little time but might greatly reduce production costs, developing a tool to help the designer to evaluate the required production cost is an important task.

Cost models for various kinds of process have been developed. A cost model for machined parts was developed by Dewhurst and Boothroyd [12]. This model requires only limited information (such as machining time, rate for machines and operators, and types of tooling materials) to estimate machining cost. It seems that most of these data can be obtained during the design stage except for the precise machining time. Therefore, this model can be used in the early cost estimation process if an approach to measure the machining time can be included.

Dewhurst and Boothroyd also developed a cost model for the injection moulding process [12]. This model estimates the machine cost, mould base cost and cavity cost to establish the manufacturing cost of injection moulded parts. Empirical data, such as the ratio of the cost required to produce a single cavity versus the cost for manufacturing multiple cavities in a single mould base, are included in this model. Another cost estimation model for injection moulded parts was proposed by McIlhenny et al [13]. In addition to the mould base and process cost, certain factors such as the material cost and maintenance cost are also included in this model. However, this model does not provide detailed rules for computing mould base and cavity cost. It seems that Dewhurst's model can provide this feature.

A model used to estimate the cost required for electronic manufacturing processes was developed by Keys et al [14]. The work focused on modelling the cost for printed wiring board assembly (PWBA). The cost of a PWBA is the sum of material cost, variable manufacturing cost such as direct labour, process materials and fuel, and fixed manufacturing cost such as management expense and taxes. Each factor can be further classified into several categories, for example, the cost of process materials is composed of the cost spent in material testing, component assembly and PWBA testing. Furthermore, in order to improve the accuracy of the cost model, the authors also developed a simulation process to ensure the reliability of the manufacturing data.

In addition to the cost evaluation methods for certain manufacturing processes, a few models were developed to estimate the cost of producing a specific category of products. For instance, research to obtain the cost information for gear drives was carried out by Bruckner and Ehrlenspiel [15]. This research was carried out through surveys in industry and several laboratory experiments. The results showed that gear drive manufacturing cost was proportional to the size of the cylindrical gear in the gear box. In addition, the set-up cost is also influenced by the gear size. A large-size gear has a larger set-up cost than a small-size gear. The authors claim that these data can be used to build a tool to assist gear drive designers to achieve a cost-effective design.

Accurate cost data is a critical factor for successfully implementing cost estimation systems. Sheldon et al. [16] proposed a framework for developing an intermediate cost database established between the cost accounting system and DFC systems. This system will analyse the cost information provided by a cost accounting system to establish the appropriate cost structures suitable for different groups of DFC users.

From the above review, it can be seen that many cost models have been developed for various kinds of application. However, if we want to implement a cost model in a DFC environment, a suitable framework which integrates all of the suitable resources is required. In this paper, an integrated framework is proposed for early cost estimating about machining operations in terms of a feature-based approach. This system tends to estimate the manufacturing cost of a design according to the shapes and precision of its features. The objective of this research is to provide an environment to assist an inexperienced designer to estimate the manufacturing cost of his/her design in order to reduce unnecessary expense.

3. Problem Description

In order to develop an integrated environment for early cost estimation, the major research problem is to find the required functions in a DFC environment. In other words, it is necessary to understand the modules which help a designer to estimate manufacturing cost during the design stage in which the demands for knowledge of the production cost can be reduced to a minimum. Based on this problem, the following issues are raised:

1. What kinds of factor, which might affect the production cost, can be determined during the design stage?

   In a product development cycle, every stage may contribute to the cost of the final product. Therefore, it is necessary to identify the factors which can be decided by designers in the initial design stage and will influence the final production cost. The major reason for this is that these identified factors can be used to link the design module with the cost analysis module so that designers can determine part of the production cost by modifying these factors.

2. How to help a designer who does not know the production cost to provide the information required by a cost evaluation system?

   As mentioned before, a designer usually focuses on the functions or shape of a design. In addition, in the current education environment, there are very few chances for a young designer to acquire knowledge about production cost. Therefore, the information required by the cost analysis system should be embedded in the data provided by the design model.

There are two major factors which can be decided during the design stage and which will affect the production cost. They are the complexity of the geometric shape and the requirements of the surface finish of a part model. In general, these factors cannot be determined independently. For instance, a part geometry might require a distinct manufacturing process and hence might require a special machine which might change the manufacturing cost. In addition, for a part model with different surface finish requirements, the manufacturing process might be completely different. However, designers usually cannot relate the change of these factors to the change in estimating manufacturing cost. Therefore, it is necessary to make designers aware of the manufacturing cost when these two factors are decided.

In order to provide the required manufacturing cost during the design stage, it is necessary to obtain the data required by the manufacturing process from a part model. Many researchers have used a feature-based approach to fulfil this requirement. That is, a part model is constructed in terms of a set of form features. A computer-aided process-planning system will analyse the geometric information of the form features and generate the required manufacturing process based on the information stored in a knowledge-based system. Therefore, the manufacturing cost for this part model can be roughly estimated if the form features can be obtained.

Based on the above discussion, there are several functions which should be provided by the integrated environment:

1. *Feature-based design function.* This function should provide a group of form features and a design interface for users to construct and modify a part model.
2. *Data extraction and analysis function.* This function should retrieve features and related information from the CAD database and perform certain analysis tasks in order to generate the manufacturing process.
3. *Cost estimation function.* This function should calculate the values of each coefficient required in the cost estimation rules and compute the possible manufacturing cost.

In order to provide these functions, the next step is to consider the molecules which should be included in this integrated environment as well as the interrelationships among these modules.

4. The Proposed System Framework

Figure 2 shows the framework of the proposed system. Basically, there are three main modules: CAD module, reference library module and analysing module. The CAD module supports the feature-based part construction and modification function for the user to perform the design task. A form feature library storing the frequently used features in the design domain is used to support the design task. The part database not only stores the B-Rep data of a part and its features but also saves other data such as the values of the parameters used in defining individual features and the precision requirements of each feature.

There are several kinds of reference data stored in the reference module. The machining specification files save the related data about the available machines in the shop such as

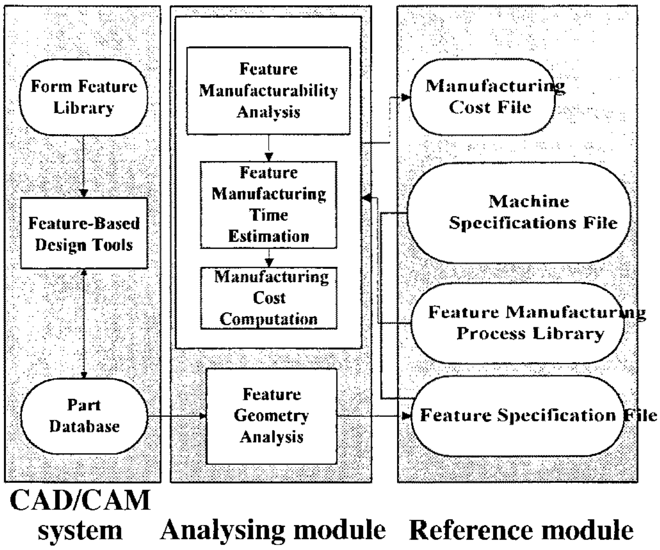

Fig. 2. The framework of the cost estimation system.

the kinds of operation that can be performed by each machine, the operating cost for each piece of equipment, and the surface finish ranges for individual machines. The feature manufacturing process library stores the required manufacturing process in order to produce certain features of different surface roughness. The manufacturing process data include the sequence of the process, as well as the required machines and the duration of each step of the process. The feature specification file saves the data about individual features of a part such as the volume and the defined parameters. Finally, the estimated manufacturing costs for each part and its features are stored in the tooling cost file. This file will prompt the users.

The major module of the proposed framework is the analysing module. There are two submodules included in it. One is the feature geometry analysis module. This module will directly or indirectly extract feature-based part data from the database of the CAD/CAM system. The retrieved data include the types of features composing a part model, the values of the parameters used to define each feature and the specified surface finish range of each feature. Other indirect information like the surface area and the volume of each feature can also be computed based on the retrieved data. These data will be stored in the feature specification file of the reference module. There are three functions in the cost analysis submodule. One analyses the manufacturability of each feature. This task is done by comparing the machining resolution of the equipment used in the final step of the operating process for each composed feature with its specified tolerance. The other function is to estimate the required manufacturing time of each feature. This will be calculated based on the material removal volume and specified surface roughness of each feature. The estimated machining time with the unit time cost of the assigned machines will be used to compute the manufacturing cost of the examined part in the manufacturing cost computation function. The computation results will be stored in the manufacturing cost file for users' reference.

5. The Feature-Based Cost Analysis Process

Based on the proposed framework, Fig. 3 shows the flowchart of the feature-based machining cost analysis process. The process can be described as follows:

Step 1: Build the part model in terms of a feature-based approach. That is, the part model is constructed by using the form features stored in the feature library.

Step 2: Specify the surface roughness of each feature of the part model.

The above two steps are carried out by the designers. The developed system will carry out the following steps:

Step 3: Retrieve the feature related information from the CAD database. These data include the feature type, the values of the parameters used to define each feature and the B-Rep data for each feature.

Step 4: Based on the retrieved data, examine the manufacturability of each feature. These include the following tasks:

4.1 For each retrieved feature type, obtain its manufacturing process from the feature manufacturing process library.

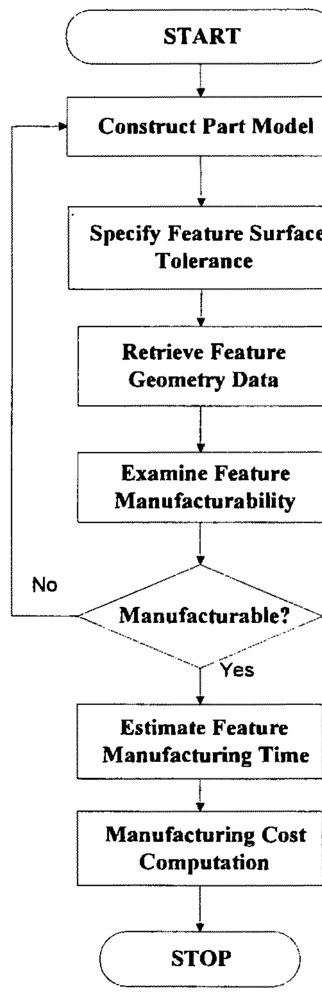

Fig. 3. The flowchart of the proposed cost analysis process.

4.2 For each process, acquire a group of suitable machines from the machine specifications file.

4.3 For those appropriate machines, select one which provides a surface finish range to meet the required surface roughness of the specific feature.

Step 5: Estimate the required machining cost for each feature. This can be roughly computed based on the following process:

5.1 For each operation of the examined feature, compute the required machining time.

Since the machining time is mainly decided by the volume of the removed material, the estimated time can be roughly computed based on the following formula:

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

Where:

T_{ij} = time required to accomplish the machining operation j of feature i

k_j = coefficient for the operation j

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

In the above equation, the variable p_{ijk} is the value of a parameter or its reciprocal for defining a certain feature such as the length, width or height of a through slot. In addition, the coefficient k_j depends on the style of the machining operation. The detailed methods for obtaining the values of these variables are described in the Appendix.

5.2 Compute the required machining cost for each operation. This can be computed as:

$$C_{ij} = M_h T_{ij} + S_h \tag{2}$$

Where:

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

M_h = unit time cost ($/min) for machine h (machine h is selected to perform operation j)

S_h = set-up cost for machine h

5.3 Estimate the required machining cost for each feature. This can be computed as:

$$FC_i = \sum_j C_{ij} \tag{3}$$

Where:

FC_i = the estimated machining cost for each feature i

Step 6: Compute the required machining cost for each part. This can be computed as:

$$TC = \sum_i FC_i \tag{4}$$

Where:

TC = the estimated machining cost for the part.

Step 7: Based on the estimated results, analyse the feasibility of manufacturing the part from the cost point of view. If the required cost cannot be accepted, then either go to Step 4.3 to re-select a machine or go to Step 1 to redesign the part.

6. The Data Flow of the Cost Analysis Process

Figure 4 shows the DFD (data flow diagram) of the proposed system. A part model is constructed by the designer in terms of the features from the form feature library. For each of these features, the designer needs to specify the type and parameters of the specific feature to obtain its geometry data from the library. In addition, the data about the location of the feature with respect to the part should also be defined.

Once a part model has been constructed, its B-Rep data and feature related information will be stored in the database of the CAD system. These data along with the tolerance of each feature will form the feature oriented part data. The parameters used to define each feature, the surface tolerance of each feature and the feature-based B-Rep data will be stored in this file. Figure 5 shows the B-Rep data structure. The difference between this structure and traditional B-Rep structure is that a layer representing the related form features is added between the part layer and the face layer. Therefore, a part is composed of a set of form features and each feature has its own B-Rep structure. The advantages of this data structure are that certain manufacturing related data such as surface area or volume of each feature can be computed based on it.

The next step is to analyse the manufacturability of each feature. The data required in this task are the manufacturing process data for each feature retrieved from the feature manufacturing process library, the specified surface roughness of each feature from the feature specification database and the surface finishing range of the available machines from the machine specification file.

Table 1 shows a sample file in the feature manufacturing process library stored for the manufacturing processes for through slot and rectangular pocket features. For each feature, the operation type for each step of the manufacturing process and its related description are saved in this library. Tables 2(*a*) and 2(*b*) show the feature related data in the feature specification database. The parameters used to define each feature are stored in Table 2(*a*). The parameter types are varied according to the different kinds of feature. For each face of a specific feature, Table 2(*a*) saves its surface roughness and identification number (face ID). The face ID can be thought of as a pointer to link the B-Rep structure of that face stored in the CAD database. Table 3(*a*) shows the sample data in the machine specification file. Three kinds of data can be obtained for each machine: the operation types that can be performed by the specific machine, the range of machining resolution for each operation type and the required cost per unit time. The machining resolution is based on CNS (China National Standard) 7688 shown in Table 3(*b*).

The major task for the function of analysing manufacturing time is to compute the required machining time for each feature. For most of the features, the required time is composed of two portions. One is the time used in removing the interior material of a specific feature. The other is the time spent in the end milling for each face of the feature. The required data to perform this task are the parameters used in defining each feature from the feature specification database. These data will

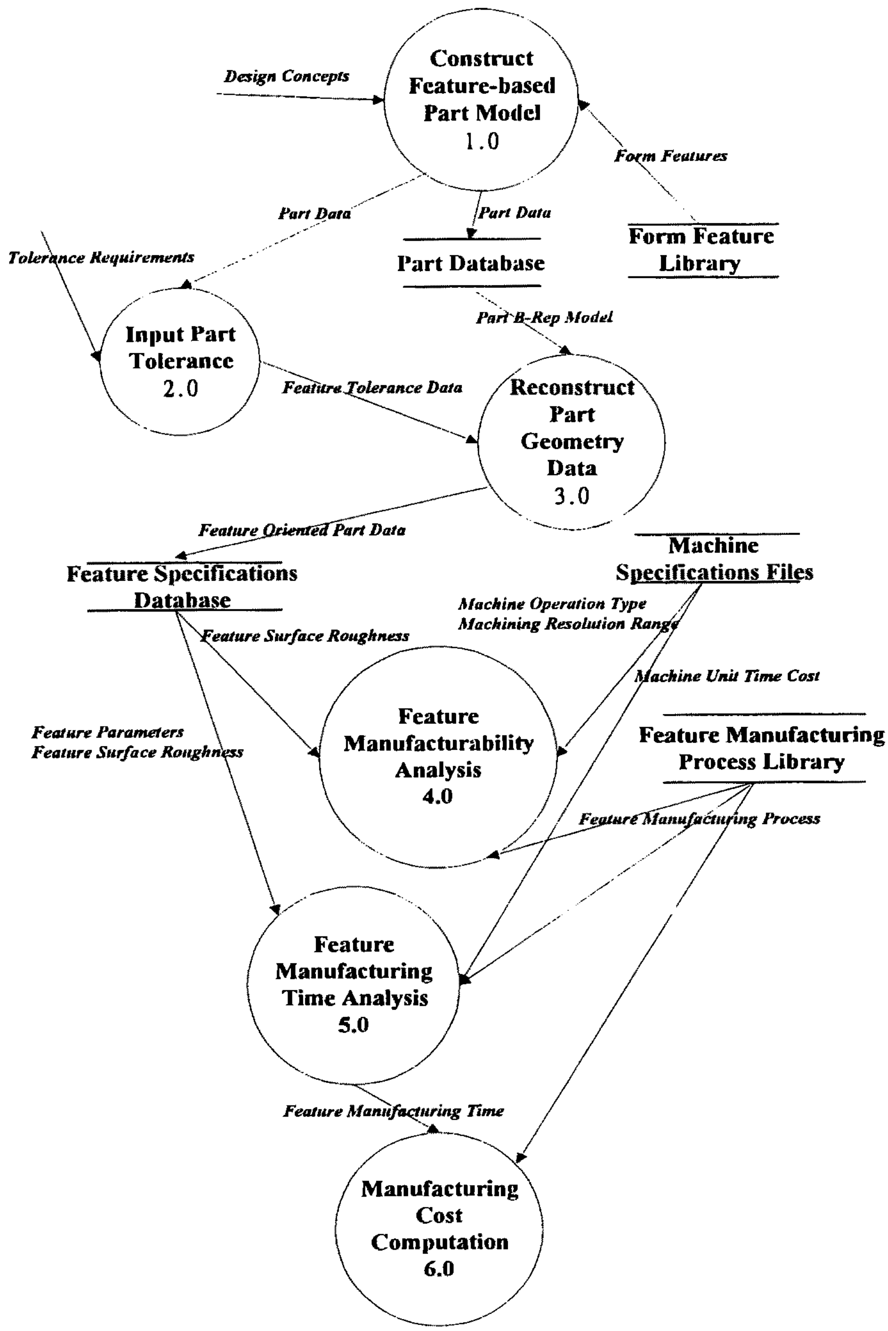

Fig. 4. The data flow diagram of the proposed system.

be used in computing the volume of the removed material for each feature. In addition, the specified roughness of each face along with its surface area, which can be computed by the retrieved B-Rep data of that face, will be used in computing the time required for the end milling of each face of a feature.

The final function is to compute the manufacturing cost of each part. The data required for this function are the manufacturing time for each feature and the unit time cost of the assigned machines. The latter information can be obtained from the machine specification file. That is, for each step in the manufacturing process of a specific feature, a machine will be assigned so that one of its available operation types and its related machining resolution will meet the requirement determined in the manufacturability analysis. The cost of this machine per unit time and the required machining time for this processing step will be used to compute the necessary manufacturing cost.

7. Implementation

The proposed system has been implemented in an SGI Indigo

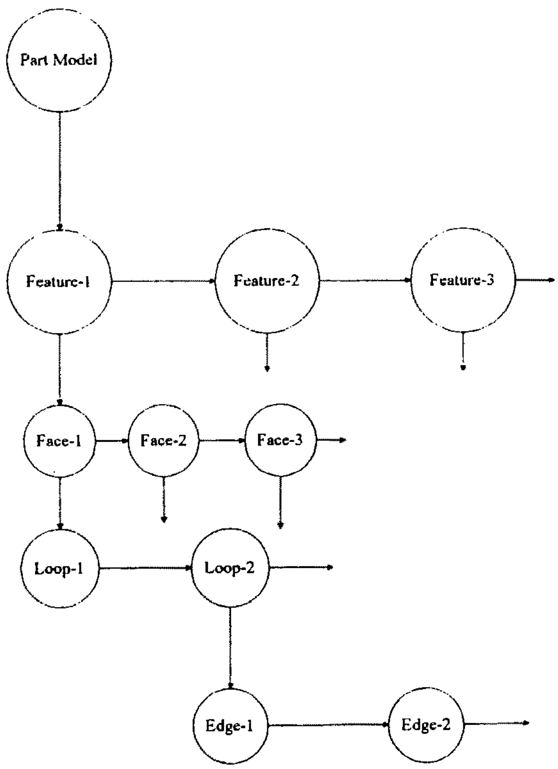

Fig. 5. Feature-based B-rep model.

Table 2. Sample files in the feature specification database.

(*a*)

Feature ID	Feature name	Dimension type	Value (mm)
94	Slot-1	Length	97.5
		Width	40
		Height	15
224	Pocket-1	Length	30
		Width	25
		Depth	15

(*b*)

Feature ID	Face ID	Surface roughness (μm)
94	10	0.2
	11	0.8
	12	0.8
224	20	0.8
	21	0.8
	22	0.8
	23	0.8
	24	0.8

Table 1. A sample file in the feature manufacturing process library.

Feature name	Feature type	Process step	Process type	Process description	Passes
Slot 1	Through slot	1	Milling	Rough mill	1
		2	Milling	Finish end mill-floor	1
		3	Milling	Finish end mill-wall	2
Pocket 1	Rectangular pocket-fully enclosed	1	Drilling	Center drill	1
		2	Milling	Plunge end mill	1
		3	Milling	Finish end mill-floor	1
		4	Milling	Finish end mill-wall	2
		5	Milling	Finish end mill-wall	2

workstation and a 486PC. Figure 6 shows the environment of the implementation of the system. A CAD system, Pro/Engineer, has been selected as the tool for part design. Pro/Engineer is a parametric design solid modelling system and uses B-Rep as its internal data representation scheme. A group of functions called Pro/Develop are provided for the user to access the Pro/Engineer database. Basically, most of the functions shown in Fig. 4 are written in the C language including Pro/Develop routines to access the Pro/Engineer database and the IRIX/Motif routines to display the cost related information.

Most files in the reference module are stored in the FoxPro database. Among those, only the feature related data stored in the feature specification database are retrieved from the Pro/Engineer database, and transferred to the PC side. The rest of the files are built in the FoxPro database. During the analysing process, relevant information will be extracted from the database through SQL and transferred to Indigo for detailed analysis and computation.

Figure 7 shows the operating modules of the system. It is composed of a few Pro/Engineer modules used to perform part construction, and several built-in modules for cost analysis.

When users enter the system through Pro/Engineer, the first function performed is *Part*. This function allows users either to retrieve a stored part model for cost analysis, or to construct a new model. For the task of constructing a new model, the next function to be carried out is *Feature*. This module will provide a feature-based environment for the user to build a part model. Once a model is made, the user will request the *Set up Precision* module to define the precision of each surface of the features. Then, the system will store certain feature related data in the FoxPro database.

Once a part model is retrieved through the *Part* function, the user can enter the *Manufacturing Cost Estimation* module

Table 3. (*a*) Sample data in the machining specification file. (*b*) Surface roughness level for CNS 7688 Standards.

(*a*)

Machine ID	Operation type	Maximum machine resolution	Minimum machine resolution	Unit time cost
M001	Milling	N9	N6	15.00
	Drilling	N8	N7	
D003	Drilling	N9	N7	10.00
B003	Boring	N5	N5	10.00

(*b*)

Roughness level	Average roughness R_a (μm)
N12	50
N11	25
N10	12.5
N9	6.3
N8	3.2
N7	1.6
N6	0.8
N5	0.4
N4	0.2
N3	0.1
N2	0.05
N1	0.025
N0	0.0125

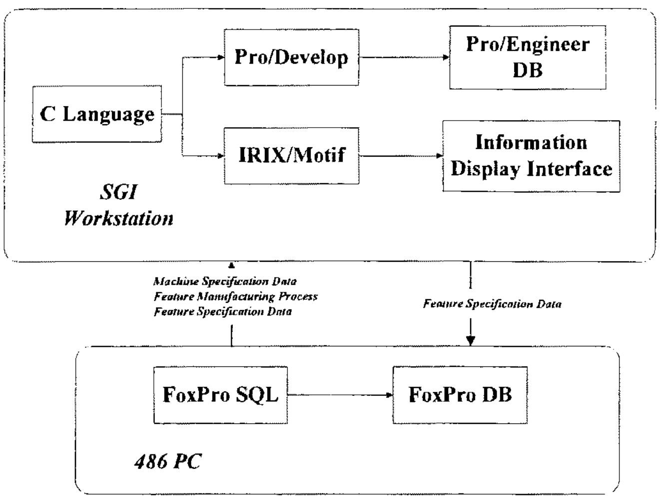

Fig. 6. The implementation environment.

to perform the cost calculation. There are three sub-modules. The *Geometric Analysis* module will retrieve the B-Rep and the values of the defined parameters about each feature to compute its surface area and volume. The tasks performed by the *Manufacturability Analysis* and the *Cost Analysis* modules have been described in the previous sections. If there is any feature which cannot be manufactured by the available equipment, the system will give warning messages and highlight the specific feature during the manufacturability analysis. Also, the system will display the estimated manufacturing cost for

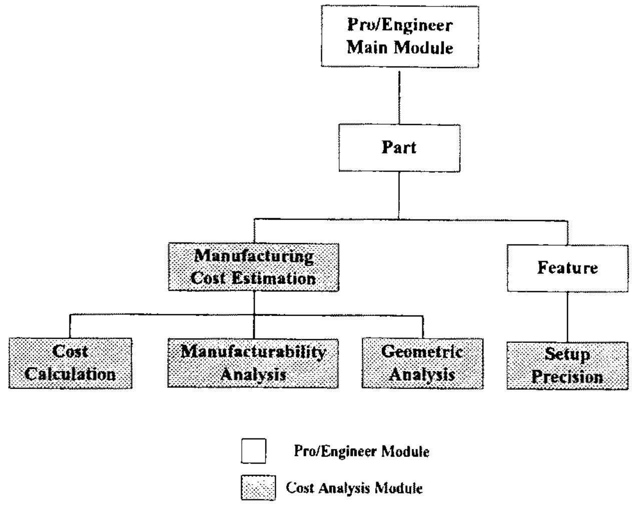

Fig. 7. The operation module of the implementation system.

the part model during the cost analysis process. The user can go back to the *Part* module to redesign the part based on the analysed results.

Figure 8 shows a sample part with four different kinds of feature: a through slot; two holes, one through step and one round-cornered pocket. Based on the indicated dimensions, Fig. 9 is the computer display for the analysed results for the sample part. Among the displayed data, the Feature-ID (IDentification number) is directly extracted from Pro/Engineer and can be used as the bridge between the analysed results and the Pro/Engineer module. The predicted tooling time for each feature is based on information such as the process planning, the values of the defined parameters of each feature and the specified surface roughness of each face of a feature.

For instance, feature "through slot" requires one pass of rough milling one pass of end-milling for its base and two passes of end milling for its two side walls (Table 1). Its length is 97.5 mm and its height is 15 mm. The surface roughness requirements for its three faces are 0.2 μm for the base and

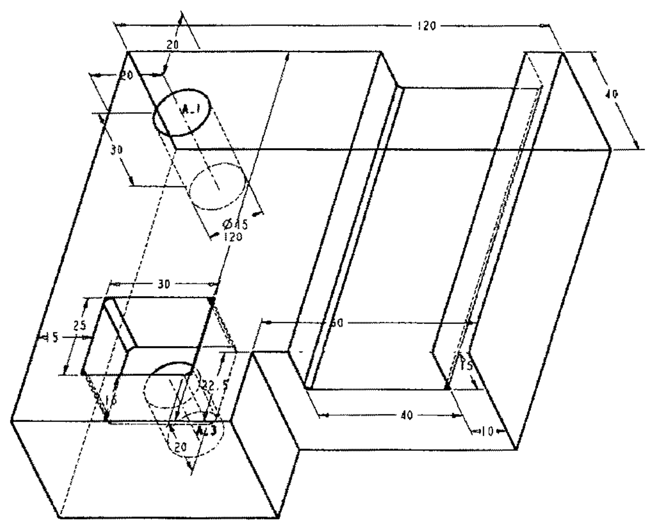

Fig. 8. The sample part.

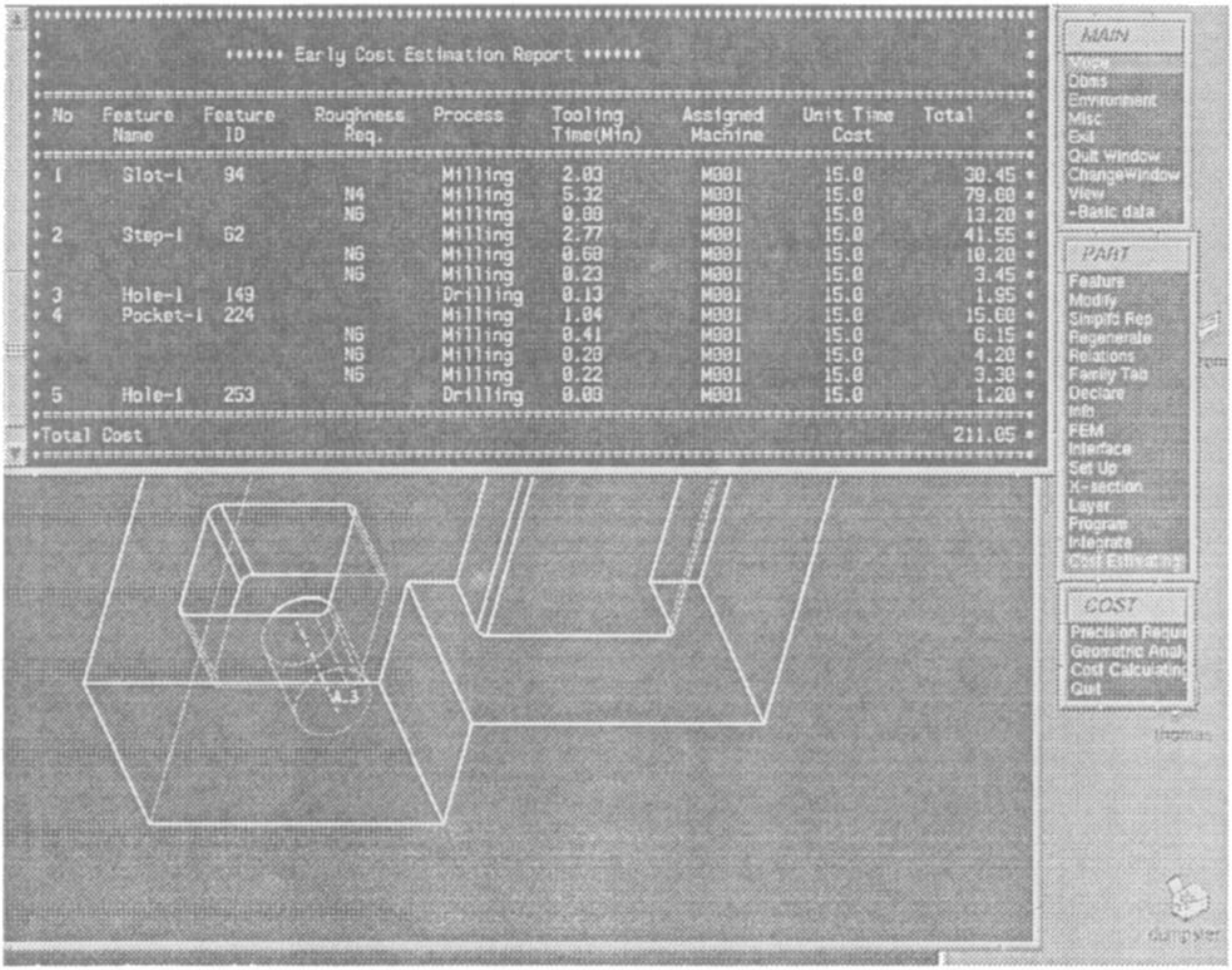

Fig. 9. The computer display of the analysed results of the sample part.

0.8 μm for the two side faces. The predicted machining time can be computer based on equation (1) and its related methods described in the Appendix.

1. For rough milling operations:

$$T = k_{rm}LH \tag{4}$$

$$K_{rm} = \frac{3}{V_f a_p} \tag{5}$$

Since for rough milling, the depth of cut a_p is assumed to be 3.8 mm and the feed speed V_f is 570 mm/min for an HSS tool at 3000 r.p.m., the predicted time is:

$$T = \frac{3 \times 97.5 \times 15}{570 \times 3.8} = 2.03 \text{ min} \tag{5}$$

2. For end milling the base of the slot:

$$T = 3\,\frac{L}{V_f} = k_{fm}L \tag{6}$$

For end milling operation, the reference feed speed V_f is 220 mm/min. In addition, the surface finish is specified as 0.2 μm. However, equation (6) is developed based on 0.8 μm surface roughness. The above equation should be adjusted based on the following equation:

$$k \propto \frac{1}{R_a} \tag{10}$$

The predicted tooling time is:

$$T = \frac{3 \times 97.5}{220} \times \frac{0.8}{0.2} = 5.32 \text{ min} \tag{6}$$

3. For end milling the wall of the slot:

$$T = \frac{L}{V_f} = k_{wm}L \tag{8}$$

Since there are two side walls in a slot, the estimated machining time is:

$$T = \frac{97.5}{220} \times 2 = 0.88 \text{ min} \tag{6}$$

Equation (4) to equation (10) can also be used to estimate the tooling time for a "pocket" feature since its required operations are similar to those for a "through slot".

Feature-IDs indicated in the cost report will be very useful for the user to adjust the design based on the analysed results. For instance, owing to over-specifying surface roughness, one specific feature might require a very long machining time and a high processing cost (such as the bottom face of the slot with N4 level in surface roughness). In this situation, the designer need only use the mouse to indicate the ID of this feature. The CAD system will highlight this feature to allow the user to perform the modification. When there are many features in a part, this function might save a lot of time in locating a specific feature.

8. Discussion

In this paper, integrated framework for estimating manufacturing cost in terms of form features is proposed. Although this work can be used to assist a designer in estimating the fabrication cost of a design during the early stage of a product development cycle, so that certain unnecessarily downstream manufacturing expenses can be reduced, several issues about the proposed framework still need attention. One is whether the machining process is appropriate as the major factor in cost estimation. In this paper, we consider only the machining process in manufacturing most of the features. However, there are many other processes used in part fabrication, so it is necessary to discuss the suitability of using the machining process as the major consideration in producing the parts. Another issue is how to assure the correctness of the analysed result. In other words, how to interpret the cost since it is just an "estimated" value?

For the first issue, although machining is only one of the much used fabrication processes, it also is the most widely used process in manufacturing industry. In addition, the machining process is usually an economical method for producing a part compared to other methods. Therefore, it is reasonable to consider the machining process as the major method in cost estimation. However, in certain situations, the machining process is not suitable for producing a feature with a very small volume or a very high surface finish requirement. One example of the former condition is a hole with a very small radius which should be produced by EDM rather than by a drilling process. Currently, these two conditions are the limitations of this research. In the developed system, only certain messages will be issued to the user to indicate that a specific feature cannot be analysed.

For the second issue, although it is difficult to judge the correctness of the analysed results, these data can be used as reference, especially for comparing the required cost between similar designs. In other words, since a major portion of new designs are modified from existing designs, this system can be used in relating the expense required for the original compared to a modified design. In addition, this system can be also used as an aid to find certain "irrational" designs. For instance, a designer might notice an unnecessary requirement for the precision of a feature owing to its high manufacturing cost.

9. Conclusions

Design for cost is an area which has attracted much attention recently. One major objective of this approach is to identify an overly expensive design during the early stage of the product development cycle. An integrated framework is proposed in this paper to achieve this objective. It includes a CAD system providing feature-based part models, a reference model containing manufacturing processes as well as cost related data, and an analysing module computing the estimated cost based on the data retrieved from the previous two modules.

The major contributions of this paper are:

1. An integrated framework to support a designer for analysing the manufacturing cost of a part during its conceptual stage is proposed.
2. A cost estimation method based on the form features and their surface roughness is proposed.
3. An implementation method which integrates commercial CAD and database packages to prove the proposed framework is proposed.

Some possible future works include:

1. *Including other manufacturing process into the reference module.* As mentioned before, a machining process has limitations in manufacturing features within certain dimensional and precision ranges. Therefore, it is necessary to include other processes in the feature manufacturing process library of the proposed framework and to develop certain reasoning methodologies to retrieve suitable manufacturing processes based on the specifications of the input features.
2. *Considering the cost required in other downstream process.* In this paper, only the cost of the manufacturing process is considered. However, the cost required in other process such as assembly, inspection and service also has a close relationship with the type of form features and their topological relationships. Basically, the above information can be decided during the design stage. Therefore, analysing the cost required in those processes in terms of those data is a feasible research topic.

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Appendix

In this paper, the major factors used to estimate the machining time of a feature are its type; process planning information; geometry data and surface finish requirements. The geometry data means the values of the parameters used to define a feature. In other words, for a specific feature, its process planning can be decided based on its type. An estimated machining time for each operation of the process will be calculated based on the values of certain parameters which can be directly extracted from a CAD database. Then, this estimated time will be adjusted according to the specified surface finish of that feature.

The required machining time for milling and drilling operations can be estimated according to the following formulae:

1. For a milling operation [17]:

$$T = t_m n_p \tag{A1}$$

and

$$t_m = \frac{L + \Delta L}{V_f} \tag{A2}$$

$$n_p = \left|\frac{\Delta h}{a_p}\right|^+ \left|\frac{w}{\alpha D}\right|^+ \tag{A3}$$

where:

- T = total time required to perform a machining operation
- t_m = time required for one pass milling
- n_p = number of passes
- L = length for one pass milling
- ΔL = overtravel for one pass milling
- V_f = feed speed
- Δh = total height of the material to be removed
- a_p = depth of cut
- $|x|^+$ = round off x to the next integer number
- W = workpiece width
- α = cutting overlap factor = effective cutting width/tool diameter = E_W/D
- D = tool diameter

In addition, several assumptions are made to estimate machining time:

1. Workpiece is assumed as low carbon alloy steel, and hardness is 175 to 225 Bhn.
2. For rough milling, a_p is assumed to be 3.8 mm for each depth of cut. According to [18], V_f should be 570 mm/min for 3000 r.p.m. HSS tools.
3. The surface finish is assumed as 0.8 μm. That is N6 level for CNS 7688.
4. Overtravel (ΔL) for each pass was not considered.
5. For rough milling a feature, the effective cutting width is assumed to be one third of the width of the removed material. In other words, three passes are required for each step of milling. Therefore, the effective cutting width can be considered as one third of the width of the milling feature ($E_w = \frac{1}{3}W$).

Based on these assumptions, equation (A1) can be simplified as

$$T \cong \frac{L\Delta hW}{V_f\, a_p \alpha D} = \frac{L\Delta hW}{V_f\, a_p E_w} = \frac{3}{V_f\, a_p} L\Delta h \cong k_{rm} LH \tag{A4}$$

and

$$kK_{rm} = \frac{3}{V_f\, a_p} \tag{A5}$$

Where:

- k_{rm} = coefficient for the rough milling operation
- L = length of the feature
- H = height of the feature

6. For end milling the bottom surface of a feature, a_p is 1.2 mm and, according to [18], V_f is 220 mm/min. The effective cutting width is still assumed to be one third of the width of the removed material. Therefore, three passes are required for each end milling operation. In addition, the total height of the material to be removed is equal to the depth of cut ($\Delta h = a_p$).
   Therefore, the required milling time is:

$$T = 3\,\frac{L}{V_f} = k_{fm} L \tag{A6}$$

and

$$k_{fm} = \frac{3}{V_f} \tag{A7}$$

Where:

k_{fm} = coefficient for end milling the floor of a feature

7. For end milling the wall of a feature, one pass is required. Therefore, the required milling time is:

$$T = \frac{L}{V_f} = k_{wm} L \tag{A8}$$

and

$$K_{wm} = \frac{1}{V_f} \tag{A9}$$

Where:

k_{wm} = coefficient for end milling the wall of a feature

The above equation is based on N6 level of surface finish. If this requirement is altered, then milling coefficient k should be adjusted as follows:

Since $f \propto R_a$ and $V_f \propto f$ [17], $\therefore$ $V_f \propto R_a$.

From equation (A9),

$$k \propto \frac{1}{V_f}, \therefore k \propto \frac{1}{R_a} \tag{A10}$$

Where:

R_a = surface finish
f = feed

Equation (A10) indicates that the milling coefficient will be increased for a tight surface finish requirement and hence might require a longer machining time.

2. *For a drilling operation* [17]:

$$T = \frac{L+\Delta L}{V_f} \tag{A11}$$

$$V_f = 0.01D \times 3000 \tag{A12}$$

Where:

L = depth of the hole
ΔL = clearance height
V_f = drilling speed for 3000 r.p.m. HSS tools (mm/min)
D = tool diameter

Two assumptions are made in order to estimate the required time for a drilling operation:

1. The diameter of the tool (D) is equal to the diameter of the drilled hole (ρ).
2. The clearance height (ΔL) for each drilling operation is not considered.

Therefore, equation (A7) can be modified as

$$T = \frac{L+\Delta L}{V_f} = \frac{L+\Delta L}{0.01D\times 3000} \cong \frac{L}{30\rho} = k_d \frac{1}{\rho} L \tag{A13}$$

and

$$k_d = \frac{1}{30} \tag{A14}$$

Where:

k_d = coefficient of a drilling operation
ρ = diameter of the drilled hole