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A knowledge-based approach to design for manufacturability

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In the light of growing global competition, organizations around the world today are constantly under pressure to produce high-quality products at an economical price. The integration of design and manufacturing activities into one common engineering effort has been recognized as a key strategy for survival and growth. Design for manufacturability (DFM) is an approach to design that fosters the simultaneous involvement of product design and process design. The implementation of the DFM approach requires the collaboration of both the design and manufacturing functions within an organization. Many reasons can be cited for the inability to implement the DFM approach effectively, including: lack of interdisciplinary expertise of designers; inflexibility in organizational structure, which hinders interaction between design and manufacturing functions; lack of manufacturing cost information at the design phase; and absence of integrated engineering effort intended to maximize functional and manufacturability objectives. The purpose of this research is to show how expert systems methodology could be used to provide manufacturability expertise during the design phase of a product. An object- and rule-based expert system has been developed that has the capability: (1) to make process selection decisions based on a set of design and production parameters to achieve cost-effective manufacture; and (2) to estimate manufacturing cost based on the identified processes. The expertise for primary process selection is developed for casting and forging processes. The specialized processes considered are die casting, investment casting, sand casting, precision forging, open die forging and conventional die forging. The processes considered for secondary process selection are end milling and drilling. The cost estimation expertise is developed for the die casting process, the milling and drilling operations, and the manual assembly operations. The results obtained from the application of the expert system suggest that the use of expert systems methodology is a feasible method for implementing the DFM approach.

Keywords: Manufacturability, cost estimation, knowledge-based systems

1. Introduction

Design for manufacturability (DFM) is an approach to design that fosters the simultaneous involvement of product design and process design. The primary objective of DFM is to produce a design at a competitive cost by improving its manufacturability without affecting its functional and performance objectives. Implementation of the DFM approach can result in a number of benefits: simplification of product design, leading to reduction in product cost; integration of parts, resulting in a reduced number of parts, which not only reduces the product cost but also improves the reliability of the product; and improved productivity through standardization of components and lower inventory (Boothroyd and Dewhurst, 1988). Further, successful implementation of the DFM approach can result in breaking down the wall that exists between design and manufacturing, improving the

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morale of design and manufacturing personnel, and reducing warranty claims (CAD/CIM ALERT, 1987). Studies at NCR and IBM have shown that the application of design for assembly analysis (DFA) has resulted in significant savings through reduction in the number of assembly parts and manufacturing costs (Dwivedi and Klein, 1986; Sprague, 1989). In addition to the direct benefits, the DMF approach also provides several indirect benefits such as improved competitive edge through shorter development time, reduction in inventory through standardization of components, and improved quality and reliability. The DFM approach enables organizations to achieve the goal of 'getting it right the first time' in order to boost their competitive edge.

The purpose of the research being presented in this paper was to explore the viability of expert systems methodology in the DFM process. In particular, we investigated the design and utility of an expert system to automate three of the critical functions in DFM: (1) performing process selection decisions based on a set of design and production parameters to achieve cost-effective manufacture; (2) estimating manufacturing cost based on the identified processes; and (3) extracting design features from solid models in a CAD system and evaluating them for manufacturability.

In the following section a knowledge-based methodology for implementing the DFM approach is presented. The architecture of the process selection and cost estimation module of the expert system is described, and the capability of the expert system is demonstrated using an actual product design. Finally, the limitations of the research and directions for future research are discussed.

2. Automating the DFM process

DFM can be implemented by drawing on a number of concepts and techniques that, collectively, allow the organization to achieve its design goals. For instance, DFM can utilize concepts and tools such as DFM guidelines for improved manufacturability (Andreasen *et al.*, 1983; Dwivedi and Klein, 1986; Billatos, 1988; Stoll, 1988; Huthwaite, 1989); design for assembly methods such as advocated by Boothroyd and Dewhurst (1983) or Hitachi (Miyakawa and Ohashi, 1986); Taguchi experiments for design optimization (Taguchi and Yuin, 1979); failure mode and effects analysis (Dussault, 1983); and design teams (Dean and Susman, 1989).

Research work in the area of computer-based simultaneous engineering has been reported in the literature. In simultaneous engineering, manufacturability has been considered as one of the life-cycle values for improvement in the early stages of design. One such methodology developed as an aid to simultaneous engineering is the design compatibility analysis developed by Ishii and others (Adler and Ishii, 1989; Ishii, 1990). This framework has been implemented as DAISIE, a knowledge-based system for performing simultaneous engineering on conceptual and layout design. The idea behind this approach is to evaluate simultaneously a candidate design from multiple viewpoints and compile a database of compatibility comments. These comments are then translated into a normalized measure of compatibility that reflects the soundness of candidate designs.

Integration and automation of DFM concepts and techniques offer the potential to enhance the DFM outcome in less time. A number of computer-based DFM software tools are available for improving the quality of product/process design decisions early in the design stage. Most software packages are spreadsheet based and address only the assembly operation in product designs. A number of expert systems for DFM have been developed, though most of them limit their scope to assembly analysis only. Though expert systems have been developed to address specific issues in manufacturability, an integrated approach to address all the major issues such as manufacturing process selection, estimation of manufacturing cost, and evaluation of product design features for manufacturability using the expert systems methodology has not been attempted thus far.

Another area of computerization for which little work has been reported in the literature is design cost estimation using knowledge-based approaches. The availability of product cost information at the design stage is a necessary prerequisite for making sound judgements concerning the choice of the most appropriate manufacturing process. The ability to perform cost estimation based on the design without detailed manufacturing planning is thus necessary. The availability of such manufacturing cost information would result in the selection of the most appropriate and cost-effective process combinations to produce a given product design.

A number of approaches for communicating production cost estimates to designers have been cited in the literature (see Ulrich and Fine, 1990). One approach aims at relying on the judgement of experienced engineers in providing manufacturing expertise. In this method, design guidelines are used to improve manufacturability of product designs which would lead to reduced product cost. Another approach relies on expert cost estimators who usually prepare cost estimates based on detailed engineering drawings. The major drawbacks of this approach are the time required for cost estimation, the need for detailed engineering information, and the variety in the accounting methods used (Harig, 1976; Matthews, 1983; Winchell, 1989).

A third approach used in manufacturing cost estimation is the use of computer programs to automate the estimation approach discussed above. These programs are mainly spreadsheet based and do not provide the flexibility to customize cost estimation systems to meet the organization's needs (Boothroyd, 1988; Quinlan, 1988). The assembly-oriented DFM approach aims at improving the ease of assembly of product designs which could lead to improvement in manufacturability and reduction in manufacturing cost as well (Boothroyd, 1988; Dewhurst, 1988; Whitney *et al.*, 1988). The weakness of this approach is the assumption that manufacturing costs are driven by assembly costs, which may not address all the issues relating to manufacturability. A fifth approach considers the total life-cycle cost of a product design rather than only the manufacturing cost. Life-cycle cost includes direct, indirect and hidden costs. The principle behind this approach is to establish mathematical relationships between product design attributes and the hidden costs such as cost of quality, cost of purchasing and inventory control, etc. (Huthwaite, 1989a, b).

Mathematical modeling and empirical formulas are the primary tools used for cost estimation. Research work reported in the literature includes Boothroyd and Dewhurst's mathematical model for estimation of machining cost and empirical model for injection molding cost estimation (Dewhurst and Boothroyd, 1987); Apgar and Daschbach's parametric cost estimation model (Apgar and Daschbach, 1987); Boothroyd and Reynolds' costing model for machining rotational components on a CNC lathe (Boothroyd and Reynolds, 1989); Knight and Poli's work on a cost analysis tool for forged components (Knight and Poli, 1985); and Poli, Fenoglio and Shunmugasundaram's work on a relative cost model for injection molding and die casting processes (Poli *et al.*, 1991). London *et al.* have developed an expert system architecture that includes a cost estimation module and a tutorial module. The main research issue was customizability of the expert system to meet an organization's needs (London *et al.*, 1987).

Perhaps the least investigated DFM area for computerization is the automation of the process of reviewing the features of a design for violations of DFM guidelines. This automation is particularly attractive in situations in which the designer is using a CAD system as the basic development tool. Computer-aided design (CAD) systems offer powerful features such as the ability to develop complex solid models and perform engineering analyses, including stress analysis, inter-object interference, collision detection and inertial analysis. However, a prominent limitation faced by designers in CAD systems is the lack of 'intelligence.' Although designs could be developed, analyzed and perfected from a functional viewpoint in CAD systems, manufacturability considerations may get little or no attention at all. As a result, product designs that are functionally sound may be developed at a high manufacturing cost. Thus, 'intelligence' should be incorporated in CAD systems, whereby product designs could not only be developed and analyzed but also evaluated for cost and manufacturability. The ability to detect design errors such as a non-standard component or a component that is difficult to manufacture, or cannot be manufactured at all, would certainly enhance the productivity of the design function.

Recent research has shown limited success in building intelligence into CAD systems to provide manufacturability feedback. Examples include an intelligent design system (IDS) (Miller and Colton, 1990; Colton and Dascanio, 1991) which integrates a CAD system, an expert system and a database system; equation-driven intelligent systems such as intelligent CAD (ICAD) and OCMS (Meerbaum *et al.*, 1987); MANNY, an intelligent system that parses a CAD database to apply Boothroyd and Dewhurst's design for assembly criteria to the evaluation of parts with one axis of insertion (Myers *et al.*, 1987).

All the methodologies and tools discussed incorporate the DFM approach and aim for improved product designs that enhance the design team's ability to design for effective quality, cost and delivery. However, implementing most of these methodologies and tools requires a high degree of involvement between the design and manufacturing personnel, interdisciplinary expertise and alterations in the organization's structure. The key to successful implementation is the development of an integrated tool by which designers could develop product designs, select appropriate manufacturing processes, estimate first-order manufacturing costs and evaluate design features for manufacturability with respect to the identified processes. The application of expert systems methodology offers considerable promise in this direction. Since the expertise involved in these activities is in the form of heuristics empirically derived over years of design and manufacturing practice, it is logical to consider an expert systems methodology to implement the DFM approach.

3. A knowledge-based approach to DFM

The work reported here is concerned with automating DFM in three primary areas: process selection, cost estimation and design review. In the remainder of this section, the manner in which the DFM process is being modeled or structured will be explained. In turn, this structure drives the formulation and design of the expert system.

An overview of the DFM approach proposed in this research is shown in Fig. 1. This approach identifies types of manufacturing processes that would lead to the cost-effective manufacturing of a proposed design and evaluates design features for manufacturability with respect to the processes identified earlier. The first step in

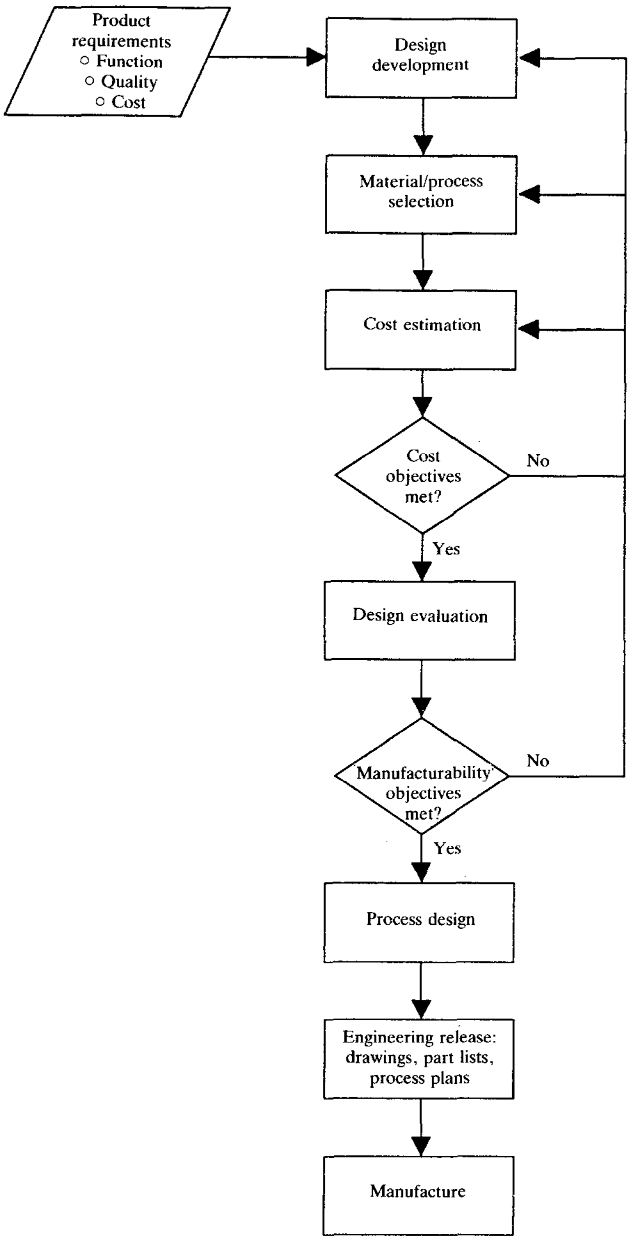


Fig. 1. Proposed DFM approach.

this approach is design development. At this stage the designer is concerned with the functional design of the product based on the product requirements. The next step involved is the selection of materials based on the product requirements and identification of the combinations of manufacturing processes for the proposed design.

The selection of manufacturing processes by which a product is to be manufactured depends on the choice of materials and limitations inherent in the processes. The selection process starts with a functionally sound design and a choice of construction material. The primary process selection is then performed based on heuristic knowledge. Primary processes determine the basic shape of the product from which other finer features are produced. Examples of primary processes include casting and forging for metals and injection molding for plastics. The heuristic knowledge involved is based on a set of design and production parameters. Each primary process has its own limitations in terms of the size of product it can handle and the level of dimensional accuracy and surface finish that can be attained on the product. The minimum production volume also has a significant impact on the process selection from the viewpoint of economy of manufacture (Niebel and Draper, 1974; Dieter, 1983). Other factors considered significant in the selection of primary processes are nature of application, minimum wall thickness and the weight of the component. The cost of primary processing is estimated using cost estimation heuristics specific to the selected process. The selection of secondary processes is then performed based on the primary process selected earlier and design features required on the product. A list of design features considered significant in the manufacture of mechanical components includes holes (through, blind, tapered and square), threads (external and internal), slots, keys and contoured (two- and three-dimensional) surfaces. The cost of secondary processing is then estimated for the identified processes.

Primary processes which are popular in the industry include casting and forging for metals, polymer processing such as injection molding for plastics, and particulate processing such as powder metallurgy for metals. Extrusion, forming and spinning are also some of the frequently used primary processes.

In this research, the selection of primary processes is limited to casting (including sand, investment and die casting) and forging (including conventional die, open die and precision forging). The selection of secondary processes is limited to end milling and drilling operations performed on a CNC milling machine. The set of design features considered includes through holes, blind holes, square holes and slots. The presence of through and blind holes indicates the need for a drilling operation; square holes and slots indicate the need for a milling operation.

The process of first-order cost estimation is then performed based on the identified process combinations. If the cost objectives are not met, the cycle of functional design, material/process selection and cost estimation is repeated.

The availability of manufacturing cost estimates is a necessary prerequisite for making judicious choices of processes to be adopted for the manufacture of a product. In this study, cost estimation expertise has been developed for the die casting process and is based on industry practice. Figure 2 gives an overview of the stages involved in performing the cost estimation for a

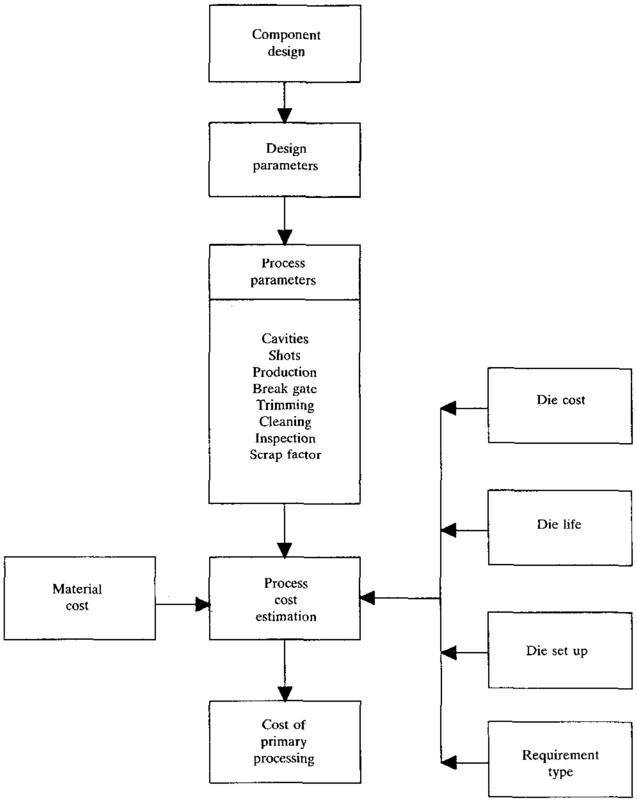


Fig. 2. Cost estimation for die casting process.

die casting process. The procedure starts with a set of design parameters that form a basis for deriving process parameters, which in turn are translated into processing cost. In the die casting process, the weight of the component is recognized as the single most influential design parameter affecting the process cost. The weight of the casting is used to estimate the process parameters, including the number of cavities and rates per hour for shots, production, breaking gate, trimming, cleaning and inspection, and scrap factor. Other factors considered in cost estimation include die life, die cost, die setup time, and component requirement – one time or recurring. The process parameter values are then translated into processing cost using the cost structure specific to the organization. The type of material used (aluminum or zinc) is used to estimate the material cost. The cost of primary processing is then computed by adding the material cost to the processing cost estimated earlier.

The cost involved in performing machining operations is based on the time required to set up the machine and the cycle time required to perform actual machining operations on each of the components in a given lot. The basic time elements involved in the estimation of setup time for a CNC milling machine include basic setup time, make part time and tolerance checking time for 'cut and try' operations. The time elements involved in the estimation of cycle time include handling, cutting, tool replacement and inspection. The estimation of setup and cycle time involves a number of parameters and is based on heuristic knowledge. The parameters considered for first-order cost estimation include the number of times the component has to be reoriented, the number of holes, the dimensions of the deepest and largest holes, and the number of sizes of holes present in the design. Setup parameters considered include type of cutting tool, type of work-holding device, and required tolerance. Based on the setup and cycle times estimated, the cost of secondary processing is computed for a production volume of Q, using the formula $C_{sp} = C_k(t_s + Qt_c)$, where C_{sp} is the total cost of secondary processing, C_k is the cost of the machine and labor per hour, t_s is the setup time, and t_c is the cycle time.

The cost involved in performing assembly operations for mechanical 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 in the case of mechanical and electrical assemblies. In this research, the cost estimation expertise is limited to manual assembly operations and is based on the Boothroyd and Dewhurst methodology. The estimation of assembly time includes two time elements, namely, handling and insertion. Handling time estimation involves product geometry, including size, thickness, alpha-symmetry and beta-symmetry of the component (Boothroyd and Dewhurst, 1983). Size and thickness refer to the length of the longest and smallest sides respectively of the smallest rectangular prism enclosing a component. Alpha-symmetry refers to the rotational symmetry of a component about an axis perpendicular to its axis of rotation. Beta-symmetry refers to the rotational symmetry of a component about its axis of insertion. Insertion time estimation involves factors related to assembly, including securing of the component after insertion, the need to be held after assembly to maintain orientation and location, and the ability of the component or the assembly tool to reach the desired location.

When the cost objectives have been achieved (see Fig. 1), the focus shifts to evaluation of product design features for manufacturability with respect to the identified processes. By extracting design features, evaluating them with respect to established guidelines for manufacturability, and redesigning the features, the designer may be able to achieve reduced manufacturing cost and improved quality in a product. The evaluation of design features for manufacturability may sometimes lead to redesign of a product or may warrant selection of different materials or processes to provide for ease of manufacture and assembly. In such cases, process selection, cost estimation and design evaluation activities may be repeated in a cycle until the cost and quality objec-

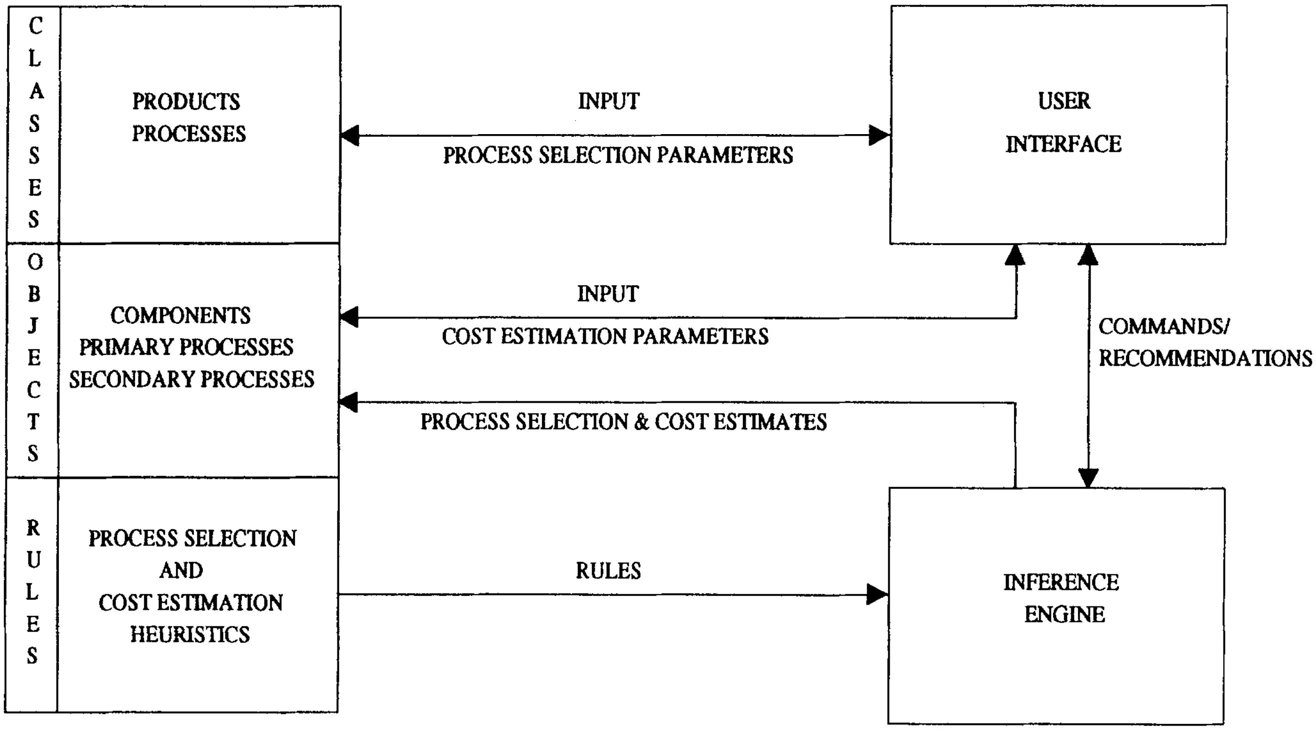


Fig. 3. Schematic diagram of the expert system.

tives are met while satisfying the design guidelines specified for the selected processes.

Process design is the next logical step after a product design has been developed, evaluated, and modified to satisfy cost, quality and manufacturability objectives. Process design activities include specification, design and layout of production equipment, process plans, inspection and testing programs, and tool and fixture design. In a computer-integrated environment, process design can be effectively carried out using part geometry information maintained in CAD databases.

The main thrust of the DFM approach is the designer's ability not only to perform functional analysis of a product design but also to improve its manufacturability by the selection of a combination of processes based on first-order cost estimates and evaluation and redesign of the design features for manufacturability. The implementation of the process selection, cost estimation and manufacturability evaluation modules in computer-aided design systems would provide designers with an integrated environment to carry out functional design, DFM analysis and process design.

4. Expert system architecture

The expert system developed is in two modules, one for process selection and cost estimation and the other for evaluation of design features for manufacturability in a CAD system. In this paper the discussion is limited to the process selection and cost estimation module.

The tool used in the development of these two modules is NEXPERT, a powerful expert system development tool built in the C language (Neuron Data, 1988). The power of this tool lies in its support for rule- and object-based knowledge representation schemes with various inference mechanisms. A schematic diagram of the expert system is given in Fig. 3. The following discussion will focus on how the knowledge representation schemes, the inference mechanism and the user interface are incorporated in the expert system.

4.1. *Knowledge representation*

A hybrid object-oriented/rule knowledge representation scheme was used in the expert system. The product itself as well as candidate manufacturing processes are represented as classes in the knowledge base; the scope of the current application is limited to the consideration of two primary processes – casting and forging. Product components and the specialized casting and forging processes considered are represented as objects belonging to their respective classes, as shown in Fig. 3. Each object has a list of properties, each representing a data type. Secondary processes such as machining are represented as sub-objects of primary processing objects; the setup

Table 1. Examples of rules

RULE PSP_8	
IF	component.application is non_critical
AND	component.prod_size is greater than or equal to 3000
AND	component.weight is less than 66 pounds
AND	component.surface_finish is greater than or equal to 32 microinches
AND	component.dimen_tolerance is greater than or equal to 0.001 inches
AND	component.wall_thickness is greater than or equal to 0.03 inches
THEN	primary process is die casting
	and create a "die_casting" object in "casting" class
RULE PSS_1	
IF	calculate_total_cost hypothesis is confirmed
AND	value of component.through_holes is "no"
AND	value of component.square_holes is "yes"
AND	value of component.blind_holes is "yes"
THEN	evaluate_secondary_process hypothesis is confirmed
	and machining operation type is milling and drilling
	and evaluate machining_process.number_setup
RULE DC_9	
IF	die_casting.prod_volume is less than or equal to 10000
AND	component.weight*1.1*die_casting.cavities is less than or equal to 8
THEN	evaluate_die_setup hypothesis is confirmed
	and 30000/die_casting.prod_volume is assigned to die_casting.die_setup_cost
RULE DC_4	
IF	die_casting.cavities is equal to 2
THEN	evaluate die_casting_scrap hypothesis is confirmed
	and die_casting.scrap_factor is equal to 0.08
RULE DC_3	
IF	die_casting.reqt_type is "onetime"
THEN	die_casting.die_cost/component.prod_vol is assigned to
	die_casting.die_amortization_cost
RULE M_7	
IF	machining_process.tool_type is "carbide"
AND	machining_process.mill_cut_time is less than 2
THEN	evaluate mill_tool_repl_time1 hypothesis is confirmed
	and calculate machining_process.mill_tool_repl_time

object is considered as a sub-object of the machining process object. This hierarchical relationship among the various objects enables property values to be inherited upwards or downwards, thus giving a powerful knowledge representation capability.

In addition to the objects, the expert system contains two categories of rules that provide process selection and cost estimation heuristics. The process selection rules are classified into two sub-groups – primary and secondary process selection. The cost estimation rules are divided into three sub-groups: die casting, machining process and assembly operation. The guidelines involved in process selection and cost estimation are stored as production or IF–THEN rules in the knowledge base. The constraints used to translate product feature and production requirements into appropriate processes and cost estimates are represented as conditions or the IF sides of rules. The conclusions or the THEN sides of rules contain hypotheses which may represent process selection and actions such as creating objects (for example, die casting) under predefined classes (casting), assigning or modifying values of an object's properties and evaluating new hypotheses. Table 1 gives examples of rules used in the expert system.

The knowledge base of the expert system has 84 rules for process selection and cost estimation. The rules were derived from knowledge obtained from the open literature as well as interviews with manufacturing experts in

Table 2. Properties and meta-slots

Examples of properties of Die_casting object		
Name	*Type*	*Description*
Break_gate_cost	Numeric (F)	Cost per piece involved in breaking gates
Cavities	Numeric (I)	Number of cavities on the die used to make the component
Clean_per_hr	Numeric (I)	Die casting cleaning rate in pieces per hour
Die_cost	Numeric (F)	Cost of the die required to make the component
Die_mtce_cost	Numeric (F)	Cost per piece involved in maintaining die
Die_setup_cost	Numeric (F)	Cost of the die setup process
Insp_and_pack_rate	Numeric (I)	Inspection and packing rate in pieces per hour

Examples of meta-slots for Die_casting object		
Property name	*Order of sources*	*If change action*
Pieces_per_hr	Number of pieces of die casting per hour = shots per hr* number of cavities	Evaluate die_casting.casting_process_cost
Machining_cost	Inherit from machining_process. machine_cost_per_piece	Evaluate assembly_time hypothesis
Metal_price	Prompt user	Evaluate die_casting.matl_cost Evaluate die_casting.break_gate_cost Evaluate die_casting.maintenance_cost
Matl_cost	Material cost = component.weight* 1.1*metal price	
Prod_volume	Inherit from component.prod_vol	

selected firms. The expert system also has four objects which represent the product, the die casting process, the machining process and the machine setups. These objects have a total of 66 properties which can have symbolic or numeric values. The properties have a total of 34 meta-slots associated with them; each meta-slot describes a set of actions to be performed if the value of its associated property is modified. Table 2 gives examples of properties and meta-slots of the die-casting object.

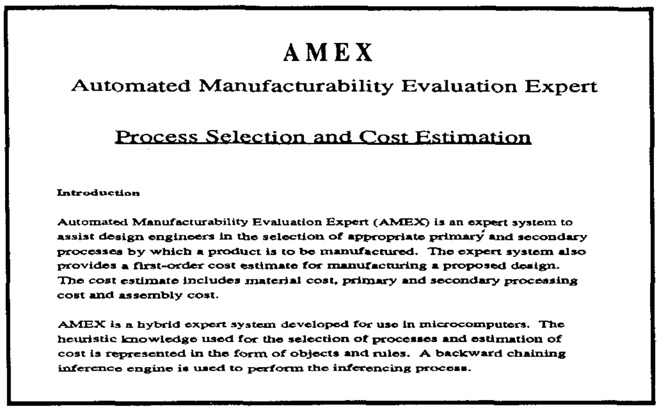
4.2. *Inference engine*

The process selection and cost estimation expert system uses a backward chaining procedure for its inferencing process. Backward chaining is a hypothesis-driven approach. The method focuses on working from a hypothesis and proceeding back to evidence.

The inference process is initiated with the testing of a user-suggested hypothesis which causes the creation of a component object, a die casting object, a machining process object and a setup object. The properties of these objects are assigned values by the execution of rules and actions contained in meta-slots. Cost estimates including primary processing cost, secondary processing cost and assembly cost are derived as the values of the properties of the objects are computed. Finally, the cost estimates are inherited upwards to the component object and the process recommendations and cost estimates are displayed to the user.

4.3. *User interface*

The expert system has an interactive menu-driven capability. Upon accessing the system, the user encounters a set of introductory screens explaining its capabilities. The user is then prompted for the values of the properties of the component object, such as geometric volume, production volume, expected surface finish, dimensional tolerance and minimum wall thickness, necessary to perform process selection. The recommendations of the system are displayed on separate screens with details of recommended process parameters. The cost estimates are displayed with breakdowns in terms of primary processing cost, secondary processing cost and assembly cost. The interaction between the system and the user is entirely through menu-driven options; the user is prompted for data inputs whenever numerical values are required. Finally, the user is provided with options to clear the working memory and restart the inference process, make a hard copy of the system recommendations, or quit the system.



AMEX

Automated Manufacturability Evaluation Expert

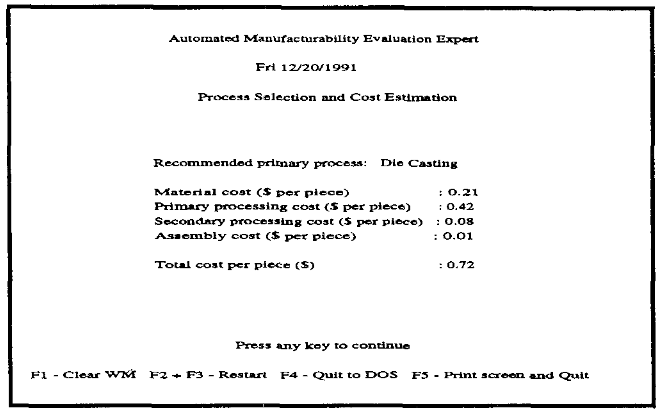
Process Selection and Cost Estimation

Introduction

Automated Manufacturability Evaluation Expert (AMEX) is an expert system to assist design engineers in the selection of appropriate primary and secondary processes by which a product is to be manufactured. The expert system also provides a first-order cost estimate for manufacturing a proposed design. The cost estimate includes material cost, primary and secondary processing cost and assembly cost.

AMEX is a hybrid expert system developed for use in microcomputers. The heuristic knowledge used for the selection of processes and estimation of cost is represented in the form of objects and rules. A backward chaining inference engine is used to perform the inferencing process.

Fig. 4. Introduction.



Automated Manufacturability Evaluation Expert

Fri 12/20/1991

Process Selection and Cost Estimation

Recommended primary process: Die Casting

Material cost ($ per piece)	: 0.21
Primary processing cost ($ per piece)	: 0.42
Secondary processing cost ($ per piece)	: 0.08
Assembly cost ($ per piece)	: 0.01
Total cost per piece ($)	: 0.72

Press any key to continue

F1 - Clear WM F2 + F3 - Restart F4 - Quit to DOS F5 - Print screen and Quit

Fig. 5. Cost estimation summary report.

5. Application of the expert system

In this section the role played by the process selection and cost estimation module of the expert system is demonstrated. The product design considered is a base hanger used in the construction of steel furniture. The material from which the base hanger is manufactured is aluminum and the volume to be produced is 5000 units year^{-1}. The nature of the application is considered to be noncritical. An application is considered critical if a component is used in areas such as high-pressure lines, nuclear plants, aircraft, missiles and instrumentation, where the consequences of failure of the component could be serious. Noncritical application refers to areas other than those indicated for critical application. The finished volume of the proposed base hanger design is 2.95 in^3 (48.3 cm^3) as obtained from the CAD database. Other relevant information obtained from the product drawing are required surface finish: 50 μin (1.3 μm); minimum section thickness: 0.125 in (3.2 mm); dimensional tolerance: 0.005 in (10.13 mm); number of holes: 1;depth of hole: 0.218 in (5.54 mm); and machining tolerance: 0.005 in (0.13 mm). All the values except the production volume are obtained from the product design drawing.

Figure 4 shows the first introductory message displayed by the system. The system then prompts the user for material group, nature of application of the component, production volume, finished volume, surface finish, section thickness and dimensional tolerance of the component. Based on the values of the design and production parameters, the system makes a recommendation that die casting is the appropriate process and that the number of cavities required in the die is 4. The user is then prompted for information on cost standards used by the organization, cost of the metal, cost of the die required to make the base hanger, and the requirement nature – one time or recurring – of the product. For the purposes of cost estimation, a 600-ton die casting machine was considered.

The expert system then shifts its focus to secondary process selection and estimation of machining and assembly cost. The user is prompted for the presence or absence of through holes, blind holes, square holes and slots to determine the machining processes required – milling or drilling or both. Information on the number of times that the component has to be reoriented, dimensions of the holes, type of cutting tool, type of work holding device and machining tolerance is then requested by the system. The machine considered is a CNC (BOSTOMATIC) milling machine. The manual assembly cost for the component is estimated by prompting the user for the 'size' and 'thickness' of the component. The user is also prompted for the alpha-symmetry and beta-symmetry of the product design and the level of difficulty involved in aligning, positioning and inserting the component during assembly. Figure 5 shows the final report prepared by the expert system for the base hanger. The total cost per unit is estimated to be 72 cents, including 21 cents for material cost, 42 cents for primary processing cost, 8 cents for machining cost and 1 cent for assembly cost.

6. Comparison of estimated and actual costs

The expert system was validated using designs for two products used in the furniture industry. Manufacturing costs were estimated for the two product designs using the expert system and compared with the actual costs.

The estimated manufacturing cost for the base hanger using the expert system is 72 cents per unit. In comparison, the actual manufacturing cost for the base hanger, as reported by the manufacturing firm from which the example was taken, is 74 cents per piece, indicating that the manufacturing cost estimate is understated by a margin of 3.86%.

Manufacturing cost was also estimated for a hinge pin.

The material cost (in this case, material of construction is zinc) and the cost of primary and secondary processing are estimated to be 48 cents per unit. The actual manufacturing cost for the product is 47 cents per unit. The manufacturing cost estimate represents a deviation of 2.30% from the actual cost.

The estimates of manufacturing cost provided by the process selection and cost estimation module of the expert system deviate from the actual manufacturing cost values by a small margin. Although this validation is based on a limited sample, the results suggest that the use of a knowledge-based approach to generate accurate early cost estimates for product designs is certainly feasible.

7. Conclusions

The major impediments to the successful implementation of the DFM approach are the emphasis on the team approach, the requirement of cross-functional and interpersonal skills for designers, and the need for structural changes in organizations. Most of the methods and tools for DFM cited in the literature insist on effective communication between design and manufacturing functions and the need for manufacturability expertise in designers. Due to divergent orientations of these functions, the realization of these requirements may involve considerable training and take longer time for organizations, thus making these methods less effective.

In comparison, a knowledge-based approach to DFM may require less time to implement as the dependence on interaction between design and manufacturing functions is drastically reduced in this approach by the availability of manufacturability expertise to designers through knowledge bases. Though the present expert system has a number of limitations, conceptually the scope of such a system is unlimited. A variety of manufacturing processes may be included in the knowledge base for process selection and cost estimation. Also, the design evaluation expertise may be developed for the complex features necessary for primary and secondary processes. A hybrid knowledge representation scheme in terms of rules and objects may be used for the loading and unloading of knowledge bases and the creation and deletion of objects as required, thus providing the capability to handle a wide variety of processes without encountering computer memory problems. The availability of manufacturability expertise in the form of rules and objects and the ability to separate domain-specific knowledge from problem-solving knowledge, thus providing designers with the flexibility to customize the heuristic knowledge required, would enhance the effectiveness of the knowledge-based approach. By the use of a robust expert system with the process selection, cost estimation and design evaluation modules integrated into a single environment and the knowledge bases refined to take care of capacity limitations, the impediments to the DFM approach would be diminished considerably. Finally, and perhaps less apparent, is the use of the expert system as a tool for training designers to incorporate manufacturability in design decisions.

In this research an integrated and comprehensive framework has been proposed for implementing the DFM approach using expert systems methodology. An expert system has been developed in two modules to enable designers to carry out process selection and cost estimation on the basis of a set of design parameters, and extraction and evaluation of design features for manufacturability with respect to the identified processes (Venkatachalam, 1990). The application of the two modules of the expert system to real-life examples demonstrates that the proposed approach using expert systems methodology is a feasible method for implementing the DFM concept.

Experimentation with the expert system demonstrates the feasibility of a knowledge-based approach to DFM. The system does, however, have a number of limitations. These limitations need to be resolved before the proposed approach can be judged as effective.

The primary issue has to do with the scope of the knowledge base. Specifically, the interdependence of material selection and process selection makes the process selection activity more complex. Although the geometry of a product is certainly one of the most important parameters that acts as a limiting restraint in the selection of processes, certain other aspects of material selection also play an important role in the selection of processes. Ordering information such as minimum order size, quantity breakpoints, sources of supply and lead time required to procure materials has considerable impact on the selection of materials and hence on the processes to be selected. Ideally, the knowledge base should cover such interrelationships among materials and process selection.

The effectiveness of a knowledge-based approach for improving the manufacturability of product designs lies in the integration of process selection, cost estimation and design evaluation activities into a single system. The ability to use a single database in a CAD system to perform process selection and cost estimation, in addition to evaluation for manufacturability, is one of the key factors in the success of this approach. Such integration would enable designers to achieve accuracy and consistency in cost and design features evaluation and reduced computing time for performing the analyses.

In the prototype expert system developed, the integration of the two modules would lead to automating some of the inputs required for process selection and cost estimation. Information on the design features of a solid model necessary to perform process selection – including volume, weight, surface area and section thickness – could be obtained directly from the CAD database, thus eliminating user inputs for these design parameters. In addition, the presence of design features that have a significant impact on the selection of primary and secondary processes – such as two- and three-dimensional contoured surfaces, undercuts, webs, slots, holes, pockets, keyways, threads and corners – may be directly inferred by extracting such features from the CAD database.

The extraction of design features could be used for cost estimation as well. The values of design parameters such as volume and weight could be used to derive process parameters specific to the process selected and subsequently translated into processing cost. The dimensions of the features to be machined could also be obtained from the mathematical blocks of the geometric entities associated with the features. The length of cut required to estimate cutting time for milling operations and diameter and depth of cut for drilling operations could be inferred from the properties associated with the features.

The estimation of assembly time and cost could be automated by the integration of the two modules. Information on the size and thickness of a rectangular envelope enclosing the solid model can be obtained by reading the CAD database. The alpha- and beta-symmetry of a solid model could be derived by interpreting the moment and products of inertia of the solid model.

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