Developing an Intelligent Education System for Design and Manufacturability Evaluation

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Abstract: **This paper addresses the concept and development of an intelligent education system in concurrent engineering environment based on object oriented technique for conventional processes such as drilling, reaming, boring, slot drilling, end milling, tapping, etc. and unconventional processes such as electrochemical machining (ECM), electro-discharge machining (EDM), electrochemical spark machining (ECSM), ultrasonic machining (USM) and wire-electro-erosion-dissolution machining (Wire-EEDM) for manufacturability evaluation and generation of alternative processes for improving product design. A feature based approach for acquiring design specification is used. Then the system automatically generates all possible alternative processes and estimates machining (cutting) cycle time, and cost, penetration rate, and efficiency for each process. The system works as a process of iterative redesign which suggests a way of using process information to find ways of reducing the cost of each design feature. It also estimates the optimum operation parameters for each process which balances between quality and manufacturing efficiency and to give designers immediate feedback about parameters such as the machining cycle time, cost and quality, efficiency and so on for optimization and give some advice to manufacturing engineers related to feed, speed, penetration rate, machining cycle time and cost saving.**

Keyword: Intelligent Education System, Design and Manufacturability Evaluation, Generating Alternative Processes, Optimization.

1- Introduction

The evolution of engineering design and manufacturing is based on man's effort to improve himself, society and the environment. Design and manufacturing are two related and necessary activities needed in order to produce goods. In traditional product development, design activities are not really separated from the manufacturing phase [1]. But in recent times, as the market place becomes global and competition for manufactured products increases, manufacturing environment is changing, design and manufacturing activities are performed by specialists and departments which are separated.

In this environment the amount of knowledge that designers should have about the new product is so vast that consideration of manufacturing constraints which require a high volume of information and knowledge become impossible. Manufacturing engineers have the same dilemma.

Although integration of design and manufacturing has not been fully achieved, Process Planning (CAPP), Computer Numerical Control (CNC), use of computers in design and manufacturing and using powerful tools such as Group Technology (GT), Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Flexible Manufacturing System, Artificial Intelligence (AI), Computer hardware and software, Case Base Reasoning (CBR) have reduced the gap between design and manufacturing. All of these tools aim towards reduction in product development time and cost, and increase the ease of production while satisfying its functional requirement. However despite the new wave of technology, design and manufacturing are not yet fully integrated. Recently many researchers state that even though the design stage may only account for a small fraction of overall product development cost, the design stage is the most expensive stage. Design accounts for only 5% of total product development cost, but over 70-80 % of total product life cycle cost and 80% of productivity and 40% of the quality of product is influenced by the design [2-5]. Therefore designers need feedback from manufacturing engineers about manufacturability of the proposed design at various stages of the design process. To provide this requirement, process planners should be able to evaluate manufacturability of the product features and reflect the effects of changes in design description of each feature on the manufacturing processes. Manufacturability considerations need deep knowledge and specialized expertise related to all the process parameters such as

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feed, cutting and spindle speed, depth of cut, feed rate for estimation of machining cycle time, cost, penetration rate for various tolerances, surface finish, and efficiency for each design feature and type of processes. Estimation of these parameters is time consuming and requires considerable amount of knowledge. There are more parameters which should be considered for unconventional processes which have been discussed for Electrochemical Machining (ECM), Electrical Discharge Machining (EDM) and Electro Chemical Spark Machining (ECSM), for Ultrasonic Machining (USM), for Electro-Discharge Texturing (EDT) and for Wire Electro Erosion Dissolution Machining (Wire-EEDM) [6-9]. One of the primary problems in integration of design and manufacturing is manufacturability evaluation and generating and evaluating of alternative processes for design features. One of the missing links between design and manufacturing is the virtual absence of any systematic approach for generating and evaluating the alternative ways to manufacture design features [10]. Most integrated design and manufacturing, try to integrate a single process plan for a given design, but in general there may be several alternative ways to manufacture each design feature. All possible alternatives should be generated and machining cycle time and cost, and penetration rate of each alternative examined, to determine how well each machining process or process sequences balances between the required quality and the need for economical and efficient manufacturing. Yet such integration needs to be sharpened to achieve better products. To address problems such as the one described above, we have developed an intelligent knowledge-based system (IKBS) for conventional and unconventional processes which generates all possible alternative machining processes for each selected design feature. It also evaluates manufacturability and estimates machining cycle time, cost and penetration rate of each process or process sequence and produces all necessary information for the product designer. This information is related to process parameter for manufacturing engineers. In order to design and manufacture a product more effectively, the ideas of concurrent engineering (CE), have evolved. CE is a new manufacturing philosophy which contains a very wide range of activities including full range of policies, techniques, practices that cause a product to be designed for the optimum manufacturing cycle time, cost efficiency and performance [11 and 12]. The issue of manufacturability evaluation is addressed by several researchers and body of research organizations [13-15]. Issues addressed include such topics as features in process-based design are explored in Cutkosky et al [16]. They described ongoing work on First-Cut, a system in which products are designed step-by-step along with plans for manufacturing them. The system is a collection of expert systems which interact with each other, and with the designer, to critique and fill in the details of evolving designs and manufacturing plans. For increasing efficiency an automating system is not the only approach. The product design plays an essential role, for increasing productivity. 80 % of a product's manufacturing productivity is determined at the design stage [4]. This idea is supported for assemblies [17]. The design for manufacturability principles has been applied to aluminium extrusions. Expert systems identify the features that cause problems in the manufacturing stage [18]. The issue of injection molding is addressed by several researchers [19]. A computer aided engineering system is described which can be used interactively for injection moulds. The quality of product design is determined based on 18 parameters, in addition to issues such as design for economical manufacture for injection mouldings [20]. Design for manufacturability for thin-walled mechanical parts and cost evaluation in injection moulding and dye casting are developed by Rosen et al [21]. They used feature based design and developed a methodology to convert a design features descriptions of a part into a tooling cost features description, then compute cost drivers from the features. Design for die casting part shape analysis for die manufacturability is addressed in Poli et al [22]. They used coding system to indicate the relative difficulty in manufacturability and any problem features of the part will be highlighted. Manufacturability issues of casting are addressed by Luby et al in [23]. They use features such as holes, buses and ribs to provide on line suggestions and manufacturing knowledge to the product designer of moulds during the design process. In this system design rules and process limitations are used to advise designers towards more manufacturable moulds. Languages for feature-based design and manufacturability evaluation are addressed by Rosen and Dixon [24]. They investigate languages for the feature-based design of thin-walled components and languages for their manufacturability evaluation in injection-moulding, die-casting, and sheet-metal- stamping processes. Based on a language of form, relationships, attributes and features are defined. Sometimes poor design parameters are selected, because of inadequate knowledge of process capabilities, good practice and jee [25]. They describe a methodology to enhance the serviceability and recyclability of products at the early stages of product development. Focus is on layout of designs which accommodate relationships between components. A prototype features based design aid for castings is developed. Macro-features such as boxes are employed to gather with co-features such as holes, ribs, and bosses) for use by the designer in creating parts [26]. A unified representation to support evaluation of designs for manufacturability: Phase I, Phase II, Phase III are reported by the National Science Foundation engineering design and manufacturing systems [27-29]. The aim of the project is to explore and to use features as a unifying concept for design representation and automatic evaluation of manufacturability and tolerance accumulation of components and assemblies at the various stages of design processes. A framework for integration of object oriented feature based CAD/CAPP/CAM system in concurrent environment is addressed [30]. It is a hierarchical framework for representation of work-pieces as an organized set of main shape features attached with some standardized features. Features in design-manufacturing integration are addressed [31]. A new approach to feature recognition on the geometric designs on surface based CAD models by reducing the search space is developed. Features are redefined in terms of spatial configurations of 3D entities called loops and links. Then in order to reduce filtering out a large part of the object's surface an interface between computer-aided design and manufacture for 2-1/2 D for prismatic part was developed [32]. Applying manufacturability evaluation for conventional process was addressed by other researchers including: parameters influence on process selection in [33]. There are currently no intelligent methods to deal with this problem for conventional processes and unconventional processes such as electrochemical machining (ECM), electro-discharge machining (EDM), and electrochemical arc machining (ECAM), ultrasonic machining (USM) and Wire-EEDM for a proposed design. A mathematical method has been introduced [10]. A computer-based concurrent engineering approach for development of an intelligent education system for manufacturability evaluation of design, generating, and evaluating alternative processes for design features is the subject of this paper.

2- Intelligent education system

The scope of the research can be described briefly as follows: An intelligent education system for manufacturability evaluation and generating and evaluating alternative process or process sequence for conventional and unconventional processes has been developed in a computer CE environment based on object oriented technique (OOT). The version three of the expert system shell (NXPERT) is used as software to develop the knowledge bases. A Hewlett Packard (HP) Model 715/80 workstation is used as hardware for the development of the expert systems. The designer can send the design specification for manufacturability evaluation and selection of optimum process at the various stages of design process. The possible alternative processes are then generated and machining cycle time and cost, penetration rate and efficiency of each process or process sequence are estimated, to determine how well each process balances the need for a quality product against the need for efficient manufacturing. Minimum machining cycle time and cost is also estimated. Redesign suggestion from manufacturability viewpoints will automatically be identified from design specification. The design part is described in terms of its features. Each feature has a geometric entity, some attributes and volume. Different classes of design features for conventional and unconventional processes are stored in the feature library. The required knowledge for performing manufacturability evaluation and generating alternative processes includes the knowledge of design representation in three dimensions in terms of features, knowledge of good practice rule, and process capabilities and knowledge of machine tool that can be used to produce a feature. Knowledge has been acquired at Keystone International Company, Engineering Machine shop laboratory of Paisley University, Mechanical and Manufacturing Engineering Department, and at electrochemical laboratory of Mechanical Engineering of the Edinburgh University. For implementation of the intelligent education system, Mycenter machining centre and EDM Sparcatron Machine at Engineering Workshop of Mechanical Department of Paisley University are used. Mazak machining centre at Keystone International Company and ECM Healy mark horizontal machine at electrochemical laboratory of Mechanical Engineering of the Edinburgh University were also part of this study. In order to evaluate manufacturability evaluation and generate and evaluate alternative processes for each design feature, machining time and cost, and penetration rate should be estimated. Machining time is one of the important factors and has a crucial role on the manufacturing requirements. It depends on man, machinery and level of automation. The degree of interaction between these depends on the level of automation and production method. In a fully automated production situation the interaction between these factors is low, but in the manual production the interaction is high. The relative time of each machining processes or process sequences are estimated. For conventional processes the following factors are considered machine set up time per batch size including time for preparation of NC programming, tool setting, and time for start and stop spindle; machining cycle time; Tool change time which refers to time required for positioning the tools for producing manufacturing features and the tool replacement time. For unconventional processes such as ECM it depends on time for setting up tooling in the machine and adjusting operation parameters, loading and unloading time, machining cycle time, inspection of tool and components, time for component washing and cleaning, general maintenance and cleaning of the machine. For ultrasonic machining, it depends on abrasive type, size, concentration, frequency and amplitude and material for tool and work-piece. All of these factors are considered in estimating machining cycle time. Machining cycle cost is another important factor for product designers as well as for manufacturing engineers. In the conventional processes, it depends heavily on material hardness, complexity of feature, geometrical tolerances, surface finish and good practice. Other costs including machine setup, machining, tool maintenance, tool replacement, labour including overhead cost and machine deracination are factors that are used to estimate total manufacturing cost. For unconventional processes such as ECM it depends heavily on the cost of electrodes, electrolyte, tool maintenance and repair, capital depreciation, electric consumption and labour cost. Detailed information for unconventional processes is in [6-9]. In order to measure manufacturability evaluation, the three elements associated with a feature is its size, manufacturing cycle time and cost are used to estimate penetration rate, and efficiency of each selected design feature for each process. All of these factors are estimated automatically by the system. A design feature may be produced by using alternative processes. These processes have been generated and machining cycle time, cost, penetration rate and efficiency of each process is estimated. Among these processes, there is one that balances the need for a quality product against the need for efficient manufacturing. The minimum machining cycle time and cost have also been estimated. This system can be used as an intelligent consulting system by product designers in the process of product design for optimization. It also can be used by manufacturing engineering for selection of optimum parameters and for training of new staff.

3- Architecture of the intelligent education system

The intelligent education system contains expertise gathered from experiment and from general knowledge about conventional and unconventional processes that can be used to generate and evaluate alternative processes at various stages of product development. It estimates machining time and cost saving for each alternative process and redesign suggestion.

3.1. Feature library, containing different classes of design features including circular holes, pockets, slots, tapped holes, counter bore holes, etc. for conventional processes and ten different classes of features including circular, square, rectangular and triangular holes, slots, pockets, turbine discs and wheels, friction discs and turning wheels, hexagonal, elliptical and pentagonal holes each of which can be produced by the system.

3.2. Work-piece material databases: Different types of material such as aluminium, carbon steel and stainless steel for conventional process and properties of 72 different types of electrically conductive material for ECM, EDM and ECAM and 7 classes of material including glasses, ceramics, hard metal with harder than 40 R_c, composite material, graphite and stone for USM and also for wire-EEDM are stored in work piece material database.

3.3. Tool material databases: The properties of 8 different types of material for electrode-tool for ECM and ECAM, and two types of material for USM, wire-tool-electrode for Wire-EEDM and different types and sizes of tools for conventional processes such as drilling, reaming, tapping, boring, end milling, slot drilling and so on are stored in tool databases.

3.4. Two different types of electrolyte are stored for ECM and ECAM, wire-EEDM and three different types of abrasive liquid for USM are stored in databases.

3.5. Process databases: Different type of process parameters for conventional machining operations such as feed speed, spindle speed, material type, cutter diameter for drilling, reaming, fine reaming, end-milling, slot drilling, rough boring, fine boring, tapping hole, countersunk, counter boring and for unconventional machining processes such as electro discharge machining (EDM), electrochemical arc machining (ECAM) and electrochemical machining (ECM) and ultrasonic machining (USM) are considered. For processes, e.g., ECM parameters such as type of electrolyte, type of material for electrode-tool, electrolyte composition, etc. are stored in process databases. For ultrasonic process, parameters such as spindle force, abrasive type, grid size, concentration, carrier fluid, frequency, power and so on and for wire-EEDM parameters such as nozzle distance, pulse on time and off time, pulse current etc. are stored in process databases.

3.6. Machine database: characteristic of one

machining centre and seven different ECM and one USM and one wire-EEDM are stored in machine databases.
3.7. Evaluation of design features based on good practice rules and processing capabilities are evaluated.
3.8. Estimation of machining cycle time and cost for conventional and unconventional processes such as ECM, EDM, ECAM, USM, and wire-EEDM. Machining cycle time and cost of each selected design feature for each alternative process based on selected material for work-piece and conditions of each process is estimated.
3.9. Redesign suggestion and estimation of cost saving: for each redesign suggestion the amount of machining time and cost saving is calculated by the intelligent system for conventional process and sent simultaneously.
3.10. The system therefore can advise designers based on the production of design features by generating and evaluating alternative processes for conventional and unconventional systems. Because a design feature may be produced by variety of alternative ways, but among the various alternative ways there is one process or process sequence that balances between the required product qualities against the need for manufacturing efficiency. The least machining cycle time and cost is also estimated for each selected design feature. In order to produce possible alternative processes. The following steps have been utilized in this research:
3.10.(a) all processes that can produce the design feature are identified.
3.10.(b) machining accuracy and surface finish achievable for each process is determined.
3.10.(c) machining cycle time, cost and penetration rate of each processes or process sequences are estimated.
3.10.(d) the machining time and cost is listed for conventional and unconventional systems in partially ordered ?.
3.10.(e) improvement of product design suggestions and the amount of machining time and cost saving is estimated.
3.10.(f) from the list of alternative process that are provided one can find the optimum process that matches the required quality. It also lists machining time and cost.

4- Parameters influencing manufacturability

When considering manufacturability, one should first check whether the selected design feature is matched with good practice and process capabilities. There are many factors influencing manufacturability for conventional processes such as dimension of the part, material type, size and shape of the work piece, dimensional, geometrical tolerances and surface finish of each design feature machining cycle time and cost. Based on the product design specification one can ask the following: are there suitable machine tools, fixture, cutting tool, stock size, material handling, and pallet changer available? Is there suitable material type and size available? Are there any alternative process(es) that can be used to produce the same feature? What is the minimum machining cycle time among the alternative processes for each design feature? What is the minimum cost for producing the feature?

5- Object Oriented Technique (OOT)

Object oriented technique is used in the development of the intelligent education system (IES). OOT is a new way of thinking for software development and programming applications. The first step in developing an IKBS is to develop a high-level, abstract view of the system to identify the relationships that exist between various elements of the system. Machining problems are usually complex. In order to represent complex problems, it is essential to represent the problems and data in more effective and efficient ways. OOT is a methodology that uses objects as the basic structure of the program and a complex problem can be expressed in terms of its objects and their relations rather than addressing the system as one large problem. It represents a hierarchical representation of the problem and the problem solving. It speeds up the development of the intelligent education system because of its inherent capability, reusability of objects and its data encapsulation.

6- Experimental verification of the system

In general, in order to find optimal processes it is necessary to employ quantitative measurement and estimating machining cycle time and cost and penetration rate for each alternative process or process sequence for each design feature. This is very difficult and time consuming. A product designer does not need the absolute cost at the early stages of the design process, because the purpose is manufacturability evaluation. In our estimation of machining time and cost model, the relative machining time and cost and penetration rate of each alternative process or process sequence for each design feature is based on various parameters. For evaluating alternative processes, it is necessary to send feedback to the designer so that the designer can modify the design to reduce machining time and cost. In this environment the computer is a tool to link design and manufacturing and manufacturing expertise can be incorporated at the various stages of the design process. As stated earlier, the object oriented technique is used to generate an alternative process in conventional and unconventional processes such as ECM, EDM, ECAM, USM and Wire-EEDM. The intelligent education system is a combination of list processing machining cycle time and cost and balancing between the required qualities and manufacturing efficiency. In order to develop the intelligent education system, there are two types of knowledge including product design knowledge, and knowledge about process and problem solving knowledge involved. The design feature is selected from the feature library. The intelligent education system is designed to evaluate manufacturability of each selected design's feature and generate and evaluate all possible alternative processes. Table 1 is a typical example which shows machining cycle time and cost of a design hole with 10mm diameter and depth and Table 2 is a typical example for pockets with width and length of 30 mm and depth of 10 mm and Table 3 is a typical example for slots with width and depth of 8 mm and length of 50 mm which can be manufactured by using various alternative processes. These alternative processes have been generated and evaluated by the IKBS. There are various parameters which influence the selection of process or process sequence such as type of design feature and its dimension, type of material, tolerances and surface finish, machining cycle time and cost. Basically for most design features, there is more than one process to make it. The optimum process is the one which balances between the required quality and the least machining cycle time and cost. This process or process sequence should be generated and evaluated and fed back to the designer to show how it is possible to reduce the machining cycle time and cost. In the variant process planning, a process planner selects a process by using the previous plan, retrieving and modifying it. This method cannot be used in concurrent engineering environment, because it can only be used when the design part is completely detailed. In the generative process planning, a process can be created by using information available in manufacturing data base without human intervention. In this study AI search approach backward chaining strategy is used to generate alternative processes and obtain the best process or process sequence based on required tolerances and surface finish. It also generates the least machining cycle time and cost. In order to verify the intelligent system described above, The Mycentre machining centre and EDM Hayes & Sparcatron machine at Paisley University and ECM Healy mark horizontal machine at Edinburgh University and Kazak machining centre at Keystone valve international company, and experimental results of ultrasonic machining are used. As shown in Table (1) there is a comparison between penetration rate and machining time and cost of hole machining between alternative experimental process with the intelligent system which generates and evaluates alternative process or process sequence.

Drilling machining cycle time of the intelligent system is 0.02 minutes faster and the penetration rate is slightly faster (0.72 mm/min) than experimental one. The tolerance and surface finish of drilling operation is poor but is the cheapest and quickest operation. For alternative sequence of drilling and reaming, the machining cycle time, cost and penetration rate of the intelligent system is equal to the experimental. In this process sequence better straightness and surface finish can be achieved. It takes more time and cost from drilling operation. The next process sequence is drilling and boring. In this process sequence, the machining time of the intelligent education system is slightly better than experimental (0.02 minute). This operation is used where better true position and tolerances are needed, or where the hole size is not standard, and no standard tool is available. The machining cycle time and cost and penetration rate of the IKBS for the three next conventional process sequences in Table 1 is slightly better than the experimental process. These process sequences are used where tight tolerances or surface finish is required. Unconventional processes such as ECM, EDM, and ECAM are used to produce complex parts in super-alloys. For unconventional process machining time and penetration rate of the EDM and process sequence of EDM and finishing EDM of the intelligent education system is slightly faster than the experimental one. The process sequence of EDM + finishing operation by EDM is used where a tight tolerances is needed. For evaluation of unconventional processes see references [6-9]. Each of the above alternative processes have been automatically generated and evaluated by the intelligent system to determine how well each one balances the need for a quality feature or product against the need for efficient manufacturing and penetration rate. Each of the alternative processes has a range of tolerances and surface finish. Second experiments were carried out to test the intelligent system. In this experiment a pocket with 30 mm width and length and 10 mm depth is produced by various alternative processes as shown in Table 2. The material of work-piece is carbon steel. The detail information related to pockets for unconventional processes are described in [6-9]. In general as discussed before, there are various alternative ways to produce a design feature, but there is one which matches between quality and required efficiency and penetration rate. All of the above alternative process or process sequences are generated and evaluated by the intelligent system. Similar alternative processes for the pocket specified above can be manufactured by a variety of other types of design features such as slots etc., and can be generated and evaluated by the intelligent system for conventional and unconventional processes to determine how well each one balances the need for a quality (tolerances and surface finish) of the feature against the need for efficient manufacturing and penetration rate. Figure (1) demonstrates the integrated intelligent education system for manufacturability evaluation and generation and evaluation of alternative process. In comparison between the machining cycle time and cost and penetration rate of manufacturing pockets mentioned above, the intelligent system has a better result than the experimental one. In this research various machining processes were used which are shown in Figures (2-6).

7- Conclusions

We have developed an intelligent education system (IES) in concurrent environment based on object oriented technique to acquire interactive design specification and generate and evaluate all possible alternative process or process sequences in conventional and unconventional processes for a given design feature. The intelligent education system consists of two modules including conventional and unconventional alternative processes. Unconventional alternative processes divided into three parts including ECM, EDM and ECSM processes and ultrasonic machining processes. A feature library is made for conventional processes and 10 different classes of design feature for unconventional processes are stored in the feature library. Three types of material for conventional systems including aluminium, carbon steel and stainless steel and 72 types of electrically conductive materials for work-piece for ECM, EDM and ECSM, and 7 classes of material for USM including glass, composite, hard metals with hardness of (40 to 60 R_c), tungsten carbide, graphite, epoxy and stone are stored in material work-piece data base. Two types of electrolyte and three typed of abrasives are stored in data bases. Various types and sized of tools including tools for drilling, reaming, boring, finish reaming, tapping, slot drilling and end milling, etc. for conventional processes and eight types of tools for unconventional processes are stored in the data bases. Description of machining centre and seven different types and sizes of unconventional machining are stored in the databases. Process parameters including feed, speed, spindle speed, cutter diameter for various types and sizes of tool for conventional machining and various process conditions for unconventional processes are considered. The intelligent system is linked with these data bases, from which advices are supplied to designers and manufacturing engineers. Specification design features are obtained by interaction with the intelligent education system. The system then advises the optimal design and process parameters which match the required quality and efficiency of operation. For each feature, operation, or process sequence the system automatically estimates machining (cutting) and cycle times and cost and penetration rate. The intelligent education system also estimates the principal processes variables and conditions such as feed, speed, spindle speed, depth of the cut, cutter diameter, penetration rate, efficiency for conventional processes, and feed rate, current density, electric power utilisation, current density, feed rate, tool electrode projected area, electrolyte composition, range of flow rate, velocity, inlet and outlet pressure, concentration, temperature efficiency and effectiveness for ECM, EDM and ECSM, Wire-EEDM and abrasive type, grid size, concentration, carrier fluid, frequency, productivity and penetration rate for ultrasonic machining. For conventional processes, in order to minimize cost, redesign suggestion is given simultaneously with machining time and cost saving for product designers. Information can help product designers modify the product design if necessary. It also provides information to show how well each process balances the need for quality product against the need for efficient manufacturing. For manufacturability evaluation the intelligent education system provides penetration rate and efficiency for all process and penetration rates and productivity for ultrasonic machining (USM). The system is used for design and manufacturing optimization and gives some advice to manufacturing engineers related to feed, speed, penetration rate, machining cycle time and cost saving. It can be used as an intelligent education system to optimize design and manufacturing parameters. It also can be used as an intelligent consultant system by product designers and manufacturing engineers**.** It is also used for training unskilled designers and manufacturing engineers for selecting optimum design and manufacturing parameters.

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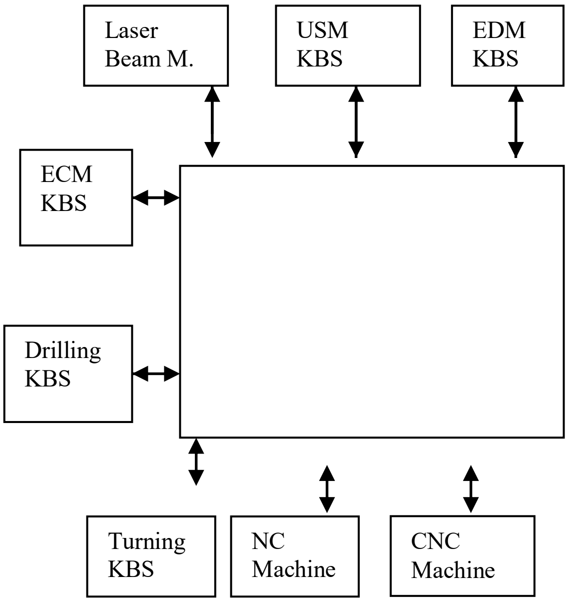


Fig 1 Integrated intelligent system for manufacturability evaluation and generation of alternative processes

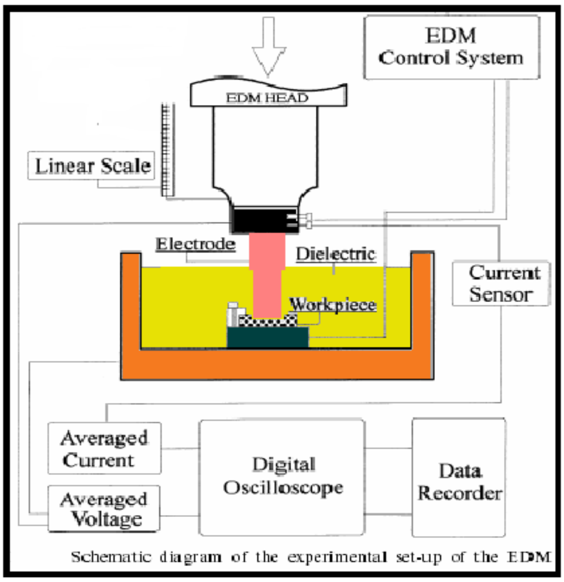
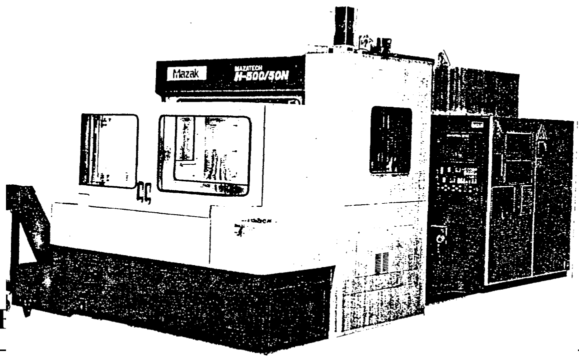


Fig 4 Electrical discharge machining



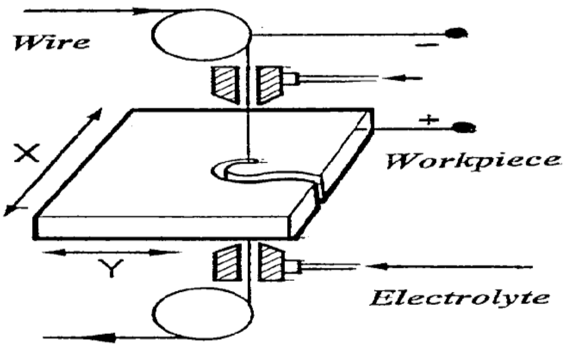


Fig 5 Wire-ECSM configurations

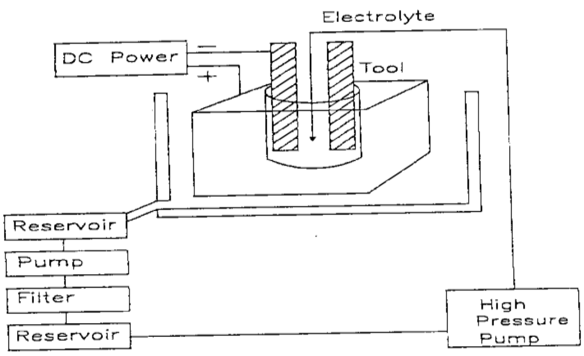


Fig 3 An electrochemical machine apparatus

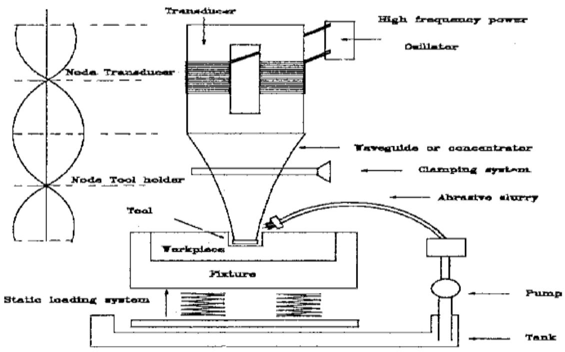


Fig 6 An ultrasonic machine apparatus

Table 1 Comparison of experimental alternative operation and intelligent system for a hole of 10 mm diameter and depth on carbon steel work-piece material, valence 2

Type of Machine	Alternative operations or (operation sequence) for Hole machining	Intelligent system (IKBS) results			Experimental investigation results		
		Machining cycle time (min)	Machining cycle cost (£)	Penetration rate (mm/min)	Machining cycle time (min)	Machining cycle cost (£)	Penetration rate (mm/sec)
Conventional alternative process							
Machine Centre	Drilling	0.56	0.10	17.86	0.58	0.10	17.14
	Drilling + reaming	1.0.0	0.17	10.00	1.0	0.17	10.0
	Drilling + boring	1.23	0.21	8.13	1.25	0.21	8.0
	Drilling+ reaming + finish ream	1.53	0.26	6.54	2.0	0.34	5.0
	Drilling+ boring+ finish ream	1.67	0.28	6.00	2.1	0.35	4.8
	Drilling+ boring+ finish boring	1.92	0.33	5.21	2.15	0.37	4.65
Unconventional alternative process							
EDM	Rough Electro-discharge mach.	34.43	1.42	0.29	35	1.45	0.28
EDM	Rough EDM +finish EDM	68.8	2.84	0.16	70.0	3.0	0.14
ECM	Electrochemical machining	6.80	1.77	1.48	8.5	2.15	1.18
ECSM	Electrochemical Spark machining	1.8	2.13	5.81	2.12	2.56	5.0
USM	Ultrasonic machining	24.02	4.08	0.42	28.0	4.9	0.35
Wire-EEDM	Wire-electro-erosion-dissolution machining	26.2	4.41	0.40	30	5.0	0.33

Table 2 Comparison of experimental alternative operation and intelligent system for a pocket with 30 mm width and length, and 10 mm depth on Carbon steel work-piece, valence 2, $NaNO_3$ electrolyte for ECM, ECSM and Wire-EEDM

Type of Machine	Alternative operations or (operation sequence) for Pocket machining	Intelligent system results			Experimental investigation results		
		Machining cycle time (min)	Machining cycle cost (£)	Penetration rate (mm/min)	Machining cycle time(min)	Machining cycle cost (£)	Penetration rate (mm/min)
Machine-Centre	Drilling	0.58	0.10	17.14			
	Drilling + slot drilling	6.07	1.03	1.65	6.20	1.05	1.61
	Drilling +end milling	6.60	1.12	1.52	6.30	1.07	1.59
	Drilling +slot drilling +finish slot drilling	7.82	1.33	1.28	7.53	1.28	1.33
	Drilling + end milling + finish end milling	8.52	1.45	1.17	8.0	1.36	1.25
EDM	Rough Electro-discharge mach.	45.0	2.24	0.22	60	3.0	0.16
	Rough EDM +finish EDM	90.0	4.48	0.11	120	5.88	0.08
ECM	Electrochemical machining	11.20	2.80	1.1	13.0	3.2	0.75
ECSM	Electrochemical Sprk machining	2.25	3.36	4.45	3.0	4.5	3.3
USM	Ultrasonic machining	275.2	46.78	0.04	325.0	55.5	0.03
Wire-EEDM	Wire-electro-erosion dissolution machining	99.25	16.87	0.10	110.0	17.5	0.09