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ORIGINAL ARTICLE

A digraph-based expert system for non-traditional machining processes selection

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Abstract The presence of a number of available non-traditional machining (NTM) processes has brought out the idea of selecting the most suitable NTM process for generating a desired shape feature on a given work material. This paper presents a digraph-based approach to ease out the appropriate NTM process selection problem. It includes the design and development of an expert system that can automate this decision-making process with the help of graphical user interface and visual aids. The proposed approach employs the use of pair-wise comparison matrices to calculate the relative importance of different attributes affecting the NTM process selection decision. Based on the characteristics and capabilities of the available NTM processes to machine the required shape feature on a given work material, the permanent values of the matrices related to those processes are computed. Finally, if some of the NTM processes satisfy a certain threshold value, those are short-listed as the acceptable processes for the given shape feature and work material combination. The digraph-based expert system not only segregates the accepted NTM processes from the list of the available processes but also ranks them in decreasing order of preference. It also helps the user as a responsible guide to select the most suitable NTM process by incorporating all the possible error trapping mechanisms. This paper takes into account some new work materials, shape features and NTM processes that have not been considered by the earlier researchers. It is further observed that the developed expert system is quite flexible and versatile as the results of the cited examples totally corroborate with those obtained by the past researchers.

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1 Introduction

With the continuous use and development of materials like titanium, stainless steel, high-strength temperature-resistant alloys, fibre-reinforced composites, ceramics, refractories and other difficult to machine alloys having higher strength, hardness, toughness and other diverse properties, there is a need for machine tools and processes which can accurately and easily machine those materials to intricate and accurate shapes. Traditional edged cutting tool machining processes are uneconomical for such materials as the attainable degree of accuracy and surface finish are quite poor. Machining of complex shapes in such materials by traditional processes is still more difficult. Other higher level requirements like low tolerance, higher production rate, automated data transmission, miniaturisation, etc., cannot be achieved by the traditional metal machining processes. To meet these demands, a different class of newer material removal processes has now emerged. These newer processes are called non-traditional in the sense that, instead of conventional cutting tools, energy in its direct form is used to remove materials from the workpiece [1, 2]. Some of these newly developed processes can also machine workpieces in areas which are inaccessible for traditional machining processes. These machining processes become still more important in the area of micro- and nano-machining. It has been observed that, in conventional machining processes where material is removed in the form of chips, attainment of the desired accuracy is a difficult task. However, such accuracy can be achieved by these non-traditional machining (NTM) processes where the material is removed in the form of atoms or molecules individually or in groups. Thus, effective utilisation of the capabilities of different NTM processes needs careful selection of the most suitable process for a given machining application. While selecting a NTM process to be employed, the following aspects are usually considered:

a) Physical parameters
b) Properties of the work material and shape feature to be machined
c) Process capability
d) Economy

These aforesaid considerations make the comparison of the machining capabilities of different NTM processes a difficult task. An increasing shortage of experienced experts in the field of NTM processes creates major hindrance in the selection of an appropriate NTM process for a given situation. Hence, there is a need for the development of a simple scientific tool to guide the users in taking a proper NTM process selection decision in order to fulfil the real-time requirements of the machining application.

Cogun [3, 4] developed a computer-aided selection procedure to aid the decision makers in selecting the NTM processes for a given part. The selection procedure uses an interactively generated 16-digit classification code to eliminate the unsuitable combinations from consideration and rank the remaining NTM processes. Only the work material and some of the process capabilities like surface finish, size tolerance, corner radii, taper, hole diameter, hole height to diameter ratio and width of cut are considered while selecting the best NTM process. Yurdakul and Cogun [5] proposed a multi-attribute selection procedure to help the manufacturing personnel in determining the suitable NTM process for a given machining application. The selection procedure first narrows down the list of NTM processes to a shortlist containing only the feasible processes. Then, it ranks the feasible NTM processes according to their suitability for a specific application. Relative weights of importance to various process selection attributes are determined using analytic hierarchy process (AHP), whereas technique for order preference by similarity to ideal solution (TOPSIS) is used to rank each of the feasible NTM processes. They developed the multi-attribute-based NTM process selection procedure taking into account two work materials (ceramic and hardened 52100 steel) and only one machining operation (cylindrical through hole drilling having L/D ratio=5.7). Seven attributes such as tolerance (T), surface finish (SF), surface damage (SD), taper (TR), material removal rate (MRR), work material (WM) and cost (C) and some useful NTM processes are considered while employing the multi-attribute approach for ranking the feasible NTM processes for a given machining application. Chakraborty and Dey [6] designed an AHP-based expert system with a graphical user interface to ease out the NTM process selection procedure. The developed expert system relies on the priority values for different criteria and sub-criteria, as related to a specific NTM process selection problem. It also depends on the logic table to identify those NTM processes that lie in the acceptability zone and then selects the best process having the highest acceptability index value. Chakraborty and Dey [7] developed an expert system based on quality function deployment for NTM process selection. A house of quality matrix is employed for comparison of the relevant product and process characteristics, and the weights obtained for various process characteristics are utilised to estimate an overall score for each of the NTM processes to select the best one. Chakraborty and Dey [6, 7] considered seven NTM processes [ultrasonic machining (USM), abrasive jet machining (AJM), electrochemical machining (ECM), electric discharge machining (EDM), electron beam machining (EBM), laser beam machining (LBM) and plasma arc machining (PAM)] from which the developed systems select the most suitable process to machine four main types of shape features (through holes, through cavities, surfacing and through cutting) on eight different types of work materials. This paper incorporates one additional NTM process, whereas the lists of work materials and shape features remain the same.

Graph theory and digraph models are logical and systematic approaches used for modeling and analysing various kinds of systems and problems in diverse fields of science and technology. This paper focuses on the development of a digraph-based expert system to aid the decision maker to select the most suitable NTM process for a given work material and shape feature combination. It considers the following eight NTM processes from which the developed expert system selects the best one:

a) AJM
b) USM
c) Chemical machining (CHM)
d) EBM
e) LBM
f) ECM
g) EDM
h) PAM.

2 NTM processes

In AJM process, a jet of inert gas consisting of very fine abrasive particles strikes the workpiece at a very high velocity (200–400 m/s), resulting in material removal through chipping/erosive action. When an abrasive particle impinges on the work surface at a high velocity, the impact causes a tiny brittle fracture and the flowing gas carries away the dislodged material. This erosive action is used for cutting, cleaning, etching, polishing and deburring operations of hard and brittle materials like glass, silicon, tungsten, ceramics, etc. USM, which is a mechanical type of machining process used to machine hard and brittle materials (conductive and non-conductive), employs a tool with high-frequency mechanical motion and abrasive slurry filling the gap between the tool and workpiece. CHM is a process to remove material by dissolution in a controlled manner from the workpiece by the application of acidic or alkaline solution called as etchant. Maskants are used to cover the surface which is not to be machined and allow the etchant not to react at that location. Material removal occurs both in the downward (depth of cut) and lateral (undercut) directions. In EBM process, a high-velocity stream of electrons generated by heating the thermo-electric cathode to a high temperature strikes the workpiece, thus transforming the kinetic energy liberated into heat and a very small amount of light energy while removing material from the work surface by melting and vaporisation. A tremendous amount of energy is released in lasers due to collision of oscillating high-energy-level atoms with electro-magnetic waves with resonant frequency. When this phenomenon is utilised for melting and vaporisation of the material from the workpiece surface, the process is called as LBM. In ECM, electrical energy is transported through metals by conduction of electrical charges from one place to another. As opposed to metallic conduction, where only electrons are the charge carriers, salt solutions also conduct electrical energy by the migration of ions in the medium. In ECM process, a single tool can be used to machine a large number of workpieces without any loss in its shape and size. In EDM process, whenever sparking takes place between two electrical contacts, a small amount of material is removed from both contacts. It is observed that sparks with short duration and high frequency are useful for efficient machining within a small area when submerged in a dielectric. In this process, the spark energy is capable of partially melting and vaporising material from a localised area on both the electrode (workpiece) and tool. Plasma, which is a glowing, ionised gas resulting from heating of a material to extremely high temperature (33,000°C), is composed of free electrons dissociated from the main gas atoms. When such a high temperature source reacts with the work material, the material melts and vaporises and, finally, is cut into pieces. The main mechanisms of material removal are heating, melting and removal of molten metal by blasting action of the plasma jet [8].

3 Digraph method

The concept of digraph elucidates the easy understandability and acceptance of the optimal criterion under investigation. Beginning from AHP to relationship diagram, these methods are found to be troublesome from the viewpoint of computational ability. Hence, the emergence of digraph and permanent of matrices come into picture. A digraph consists of a set of nodes $N=\{n_i\}$ (i=1, 2,…, M) and a set of directed edges $E=\{e_{ij}\}$. A node n_i represents ith selection criterion/attribute and edges represent the relative importance among the attributes. The total of nodes, M, is equal to the number of selection criteria considered. If a node i has relative importance over another node j in the selection process, a directed edge or arrow is drawn from node i to node $j(e_{ij})$. If j is having relative importance over i, then a directed edge or arrow is drawn from node j to node $i(e_{ji})$. The digraph basically depicts the graphical representation of the interdependence between various decision attributes taken two at a time and their relative importance for quick visual perception [9–15]. As the number of nodes and their interrelations increases, the digraph becomes complex. In such a case, simple analysis of the digraph is expected to be difficult and complex. To overcome this problem, the digraph is usually represented in a matrix form [16]. Matrix representation of a digraph gives one-to-one representation, taking all the attributes (A_i) and their relative importance (a_{ij}) into account. The matrix B for a digraph can be represented as:

$$B = \begin{bmatrix} A_i & a_{12} & a_{13} & \cdots & \cdots & \cdots & a_{1M} \\ a_{21} & A_2 & a_{23} & \cdots & \cdots & \cdots & a_{2M} \\ a_{31} & a_{32} & A_3 & \cdots & \cdots & \cdots & a_{3M} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{M1} & a_{M2} & a_{M3} & \cdots & \cdots & \cdots & A_M \end{bmatrix} \qquad (1)$$

where A_i is the value of the ith attribute represented by node n_i and a_{ij} is the relative importance of the ith attribute over the jth one represented by the edge e_{ij}. The permanent of the matrix B can be defined as a function which leads to a better visualisation of digraph theory. In the expression for permanent of the matrix, as no negative sign appears, no information is lost. This permanent function is the determinant of a matrix, considering all the terms as positive.

4 Digraph for NTM process selection

An effective selection procedure requires the consideration of various quantitative and qualitative factors. The objective of a NTM process selection approach is to identify the NTM process selection attributes/criteria and obtain the most appropriate combination of those attributes in light of real-time requirements. A NTM process selection attribute can be defined as a factor that governs the selection procedure of a NTM process for a given machining application. The NTM process selection criteria basically include workpiece material, power consumption, cost, process capability attributes like MRR, tolerance, surface finish, surface damage, corner radii, taper, hole diameter, depth/diameter ratio (slenderness ratio) for cylindrical holes, depth/width ratio (aspect ratio) for cavities and pockets, width of cut, heat affected zone, exterior and interior profiles [15], etc. Almost all the attributes may affect the machining performance of the NTM processes to some extent, but only six most significant attributes, such as tolerance and surface finish (TSF), MRR, power requirement (PR), C, shape feature (F) and work material type (M), are incorporated in the digraph-based NTM process selection procedure. Considering all the process attributes in the digraph and matrix method will also cause the computation of permanent values of the matrices to be a difficult and tedious task [17]. These six attributes are chosen in such a way that they will cover all the other non-dominating attributes as sub-attributes [6]. The NTM process selection digraph is developed based on these six attributes, as shown in Fig. 1.

The NTM process selection digraph exhibits the NTM process selection attributes and their interrelationship. As six NTM process selection attributes are considered, there are six nodes in the developed digraph. MRR is relatively more important than PR in NTM process selection. However, PR is also important even though less important than MRR. Thus the relative importance exists between these two attributes in both directions. Similarly, the relative importance can also be represented between the other attributes. The NTM process selection digraph can be expressed in a matrix form, as given below:

$$D = \begin{bmatrix} & \text{TSF} & \text{MRR} & \text{PR} & \text{C} & \text{F} & \text{M} \\ \text{TSF} & A_1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ \text{MRR} & a_{21} & A_2 & a_{23} & a_{24} & a_{25} & a_{26} \\ \text{PR} & a_{31} & a_{32} & A_3 & a_{34} & a_{35} & a_{36} \\ \text{C} & a_{41} & a_{42} & a_{43} & A_4 & a_{45} & a_{46} \\ \text{F} & a_{51} & a_{52} & a_{53} & a_{54} & A_5 & a_{56} \\ \text{M} & a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & A_6 \end{bmatrix} \quad (2)$$

The NTM process selection function for matrix Eq. 2 can be written [13] as follows:

$$\begin{aligned}
\mathrm{per}(D) = {} & \prod_{i=1}^{6} A_i + \sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{ji})A_kA_lA_mA_n \\
& + \sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji})A_lA_mA_n \\
& + \Bigg(\sum_{i=1}^{3}\sum_{j=i+1}^{6}\sum_{k=j+1}^{5}\sum_{l=i+2}^{6}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{ji})(a_{kl}a_{lk})A_mA_n \\
& + \sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{jk}a_{kl}a_{li} + a_{il}a_{lk}a_{kj}a_{ji})A_mA_n\Bigg) \\
& + \Bigg(\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{5}\sum_{m=l+1}^{6}\sum_{n=1}^{6} (a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji})(a_{lm}a_{ml})A_n \\
& + \sum_{i=1}^{2}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=j+1}^{6}\sum_{n=1}^{6} (a_{ij}a_{jk}a_{kl}a_{lm}a_{mi} + a_{im}a_{ml}a_{lk}a_{kj}a_{ji})A_n\Bigg) \\
& + \Bigg(\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{jk}a_{kl}a_{li} + a_{il}a_{lk}a_{kj}a_{ji}) \\
& \times (a_{mn}a_{nm}) \\
& + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6} (a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji}) \\
& \times (a_{lm}a_{mn}a_{nl} + a_{\mathrm{ln}}a_{nm}a_{ml}) \\
& + \sum_{i=1}^{1}\sum_{j=i+1}^{6}\sum_{k=i+1}^{3}\sum_{l=i+2}^{6}\sum_{m=k+1}^{5}\sum_{n=k+2}^{6} (a_{ij}a_{ji})(a_{kl}a_{lk})(a_{mn}a_{nm}) \\
& + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=i+1}^{6}\sum_{n=j+1}^{6} \\
& \times (a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni} + a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji})\Bigg)
\end{aligned} \quad (3)$$

Equation 3 is the complete expression for the considered NTM process selection problem, as it considers the presence of all the attributes and possible relative importance between the attributes. The terms in the above expression are the sets of distinct diagonal elements and loops of off-diagonal elements of different sizes.

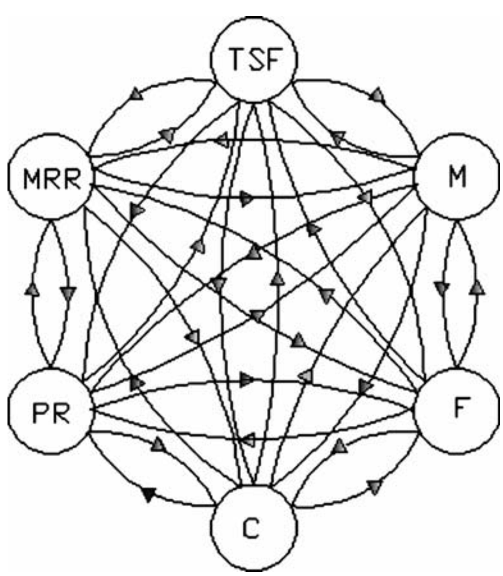

Fig. 1 NTM process selection digraph

5 Digraph-based expert system for NTM process selection

Lack of knowledge regarding the capabilities of different NTM processes, uncertainties related to various cost elements while operating those NTM processes, complex process characteristics and shortage of information regarding the applicabilities of the NTM processes often make the selection of the most suitable NTM process for a given work material and shape feature combination a challenging task. An expert system is a computer programme intended to embody the knowledge and ability of an expert in a certain domain. The primary goal of an expert system is to make expertise available to the decision makers who need answers quickly. There is never enough expertise to go around—certainly it is not always available at the right place and the right time. Expert knowledge is a combination of a theoretical understanding of the problem and a collection of heuristic problem-solving rules that experience has shown to be effective in the domain. Expert systems are constructed by obtaining this knowledge from a human expert and coding it into a form that a computer may apply to similar problems. This reliance on the knowledge of a human domain expert for the system's problem solving strategies is a major feature of expert system. The basic components of an expert system are a knowledge base (KB) and an inference engine. The information to be stored in the KB is obtained by interviewing people who are experts in the area in question. The database related to the applicability of different NTM processes to machine various shape features on different work materials is retrieved using the inference engine, which enables us to draw deductions regarding the selection of the most appropriate NTM process for a given application.

The developed digraph-based expert system for NTM process selection considers six different attributes that directly influence the NTM process selection problem. Being an expert system, it acts as a decision aid to select the most suitable NTM process for a given work material and shape feature combination. The NTM process selection is based on the construction of three matrices, i.e. (a) comparison matrix between different selection attributes, (b) normalised matrix and (c) final selection matrix. The features of a digraph include the concept of the permanent of a matrix that makes the comparison between various attributes easier and helps to clearly analyse the attributes affecting the NTM process selection decision. These attributes can be related to the following NTM process characteristics that are taken into account while fulfiling the requirements of the manufacturing personnel.

(a) Application:

1. Material application: It is mainly concerned with how easily a specific work material can be machined using a particular NTM process.
2. Shape application: This is the capability of a NTM process to generate a specific shape feature on a given work material that it can machine.

Table 1 Relative importance of the NTM process selection attributes

Class description	Relative importance (a_{ij})
One attribute is exceptionally less important than the other	0.045
One attribute is extremely less important	0.135
One attribute is very less important	0.255
One attribute is less important	0.335
One attribute is slightly less important	0.410
Two attributes are equally important	0.500
One attribute is slightly more important	0.590
One attribute is more important	0.665
One attribute is much more important	0.745
One attribute is extremely more important	0.865
One attribute is exceptionally more important than the other	0.955

(b) TSF: It relates to the capability of a NTM process, stating how closely the process can achieve the required TSF on the work material.
(c) MRR: It is the most important criterion leading to the fact that higher MRR leads to lower machining time, and the effectiveness of a NTM process is usually measured in terms of MRR.
(d) PR: It deals with the power consumption of the machining set-up for a particular NTM process.
(e) Cost: It is concerned with the initial investment and acquisition cost needed to install a NTM process-based machining system for a given application.

These NTM process characteristics are assumed to be independent of each other to avoid repetition in analysis.

The NTM process selection matrix includes both the quantitative and qualitative attributes. The value of A_i can be obtained from specified or experimental data. When quantitative values of various attributes are available, the assigned values are estimated by v_{ij}, where v_i is the measure of the attribute for the ith alternative and v_j is the measure of the attribute for jth alternative, which has the highest measure among the considered alternatives [11]. This ratio is applicable only for beneficial attributes like MRR. Non-

Table 2 Pair-wise comparison matrix for the NTM process selection attributes

Attribute	TSF	MRR	PR	C	F	M
TSF	–	0.590	0.865	0.665	0.865	0.865
MRR	0.410	–	0.745	0.590	0.745	0.865
PR	0.135	0.255	–	0.335	0.665	0.865
C	0.335	0.410	0.665	–	0.745	0.665
F	0.135	0.255	0.335	0.255	–	0.745
M	0.135	0.135	0.135	0.335	0.255	–

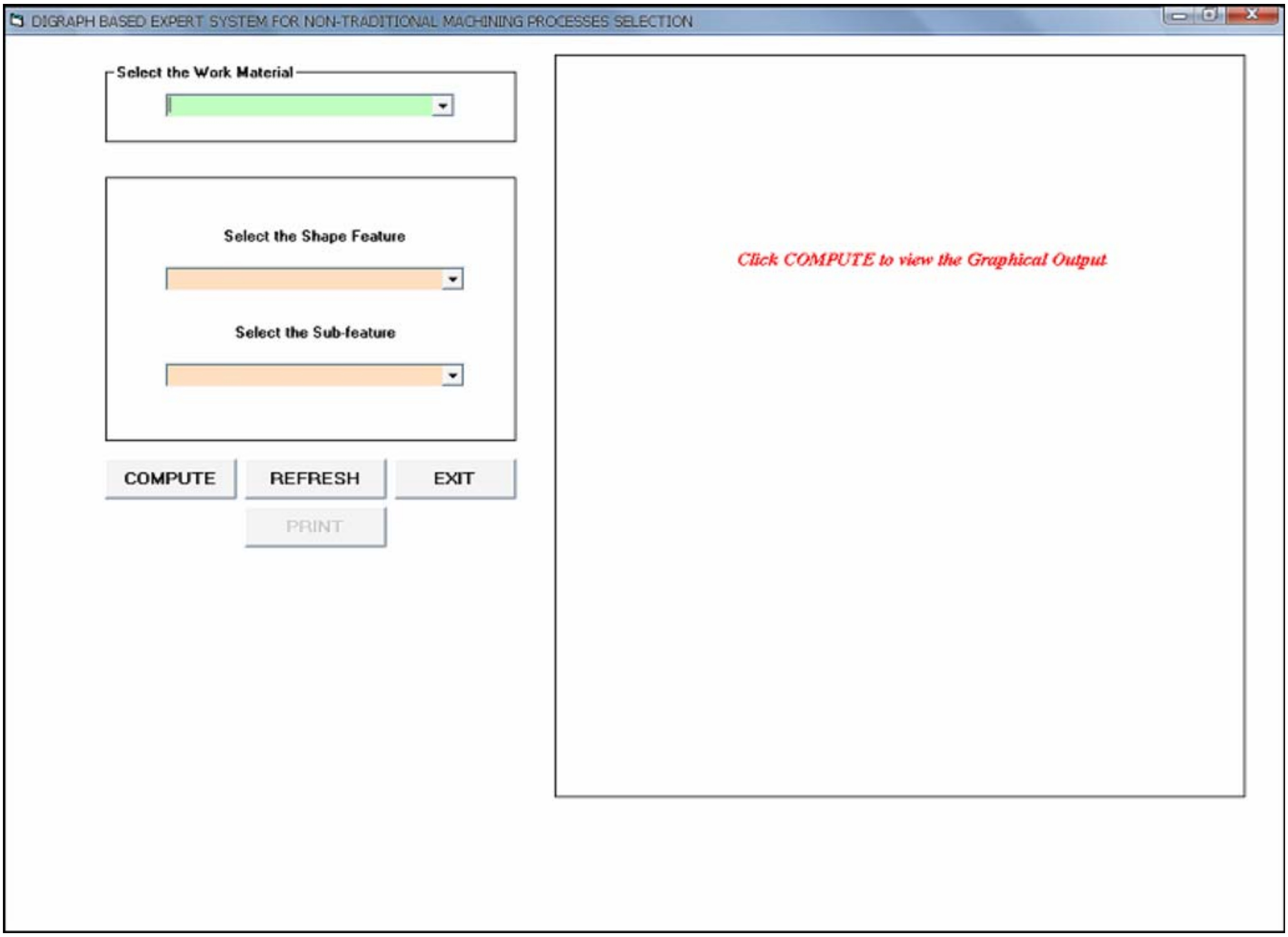

Fig. 2 Home window of the expert system

beneficial attributes, such as PR, cost and TSF, are those whose lower measures are desirable and the normalised values assigned to the alternatives are calculated as v_{ji}. If quantitative values are unavailable, a ranked value judgment on a scale can be employed. In this NTM process selection procedure, a five-point scale is adopted for judging the performance of the alternative processes with respect to cost, shape feature and work material type. Sometimes, a ranked value judgment on a fuzzy conversion scale is also used. Rao [13] considered an 11-point scale for calculating the flexible manufacturing system selection index, as given in Table 1. The same scale is also employed here for pair-wise comparing the NTM process selection attributes. Once a qualitative attribute is represented on a scale, then the normalised values of the

Table 3 Quantitative values of different NTM process selection attributes for example 1

NTM process	TSF (μm)	MRR (mm^3/min)	PR (kW)	C	F	M
AJM	2.5	0.8	0.22	1	1	4
USM	1.0	300	2.4	2	1	3
CHM	3.0	15	0.4	3	4	5
EBM	2.5	1.6	0.2	4	4	4
LBM	2.0	0.1	1.4	3	5	4
ECM	3.0	1,500	100	5	1	4
EDM	3.5	800	2.7	3	1	4
PAM	5.0	75,000	50	1	1	5

Table 4 Normalised values of the attributes for example 1

NTM process	TSF	MRR	PR	C	F	M
AJM	0.4000	0.000010	0.9091	1.0000	0.2000	0.8000
USM	1.0000	0.004000	0.0833	0.5000	0.2000	0.6000
CHM	0.3333	0.000200	0.5000	0.3333	0.8000	1.0000
EBM	0.4000	0.000020	1.0000	0.2500	0.8000	0.8000
LBM	0.5000	0.000001	0.1428	0.3333	1.0000	0.8000
ECM	0. 3333	0.020000	0.0020	0.2000	0.2000	0.8000
EDM	0.2857	0.010670	0.0741	0.3333	0.2000	0.8000
PAM	0.2000	1.000000	0.0040	1.0000	0.2000	1.0000

Table 5 Permanent values related to the NTM processes for example 1

NTM process	Permanent of matrix	Average
AJM	5.5608	4.6450
USM	4.1233	
CHM	5.2072	
EBM	5.7866	
LBM	4.7814	
ECM	3.0673	
EDM	3.2183	
PAM	5.4149	

Table 6 NTM process selection attributes for example 2

NTM process	TSF (μm)	MRR (mm^3/min)	PR (kW)	C	F	M
AJM	2.5	0.8	0.22	1	1	4
USM	1.0	300	2.4	2	1	4
CHM	3.0	15	0.4	3	1	4
EBM	2.5	1.6	0.2	4	4	4
LBM	2.0	0.1	1.4	3	4	4
ECM	3.0	1,500	100	5	5	4
EDM	3.5	800	2.7	3	1	5
PAM	5.0	75,000	50	1	5	4

attribute assigned for different alternatives can be determined in the same way as that for the quantitative attributes. It is worth mentioning here that any scale for A_i and a_{ij} can be chosen. As these are relative scales, the final ranking will not change. Based on the ranked values, as shown in Table 1, the pair-wise comparison matrix exhibiting the relative importance of different NTM process selection attributes is constructed, as given in Table 2.

In this digraph-based approach, the following materials are taken into account that can be machined using the considered NTM processes:

(a) Aluminium
(b) Steel
(c) Super alloys
(d) Titanium

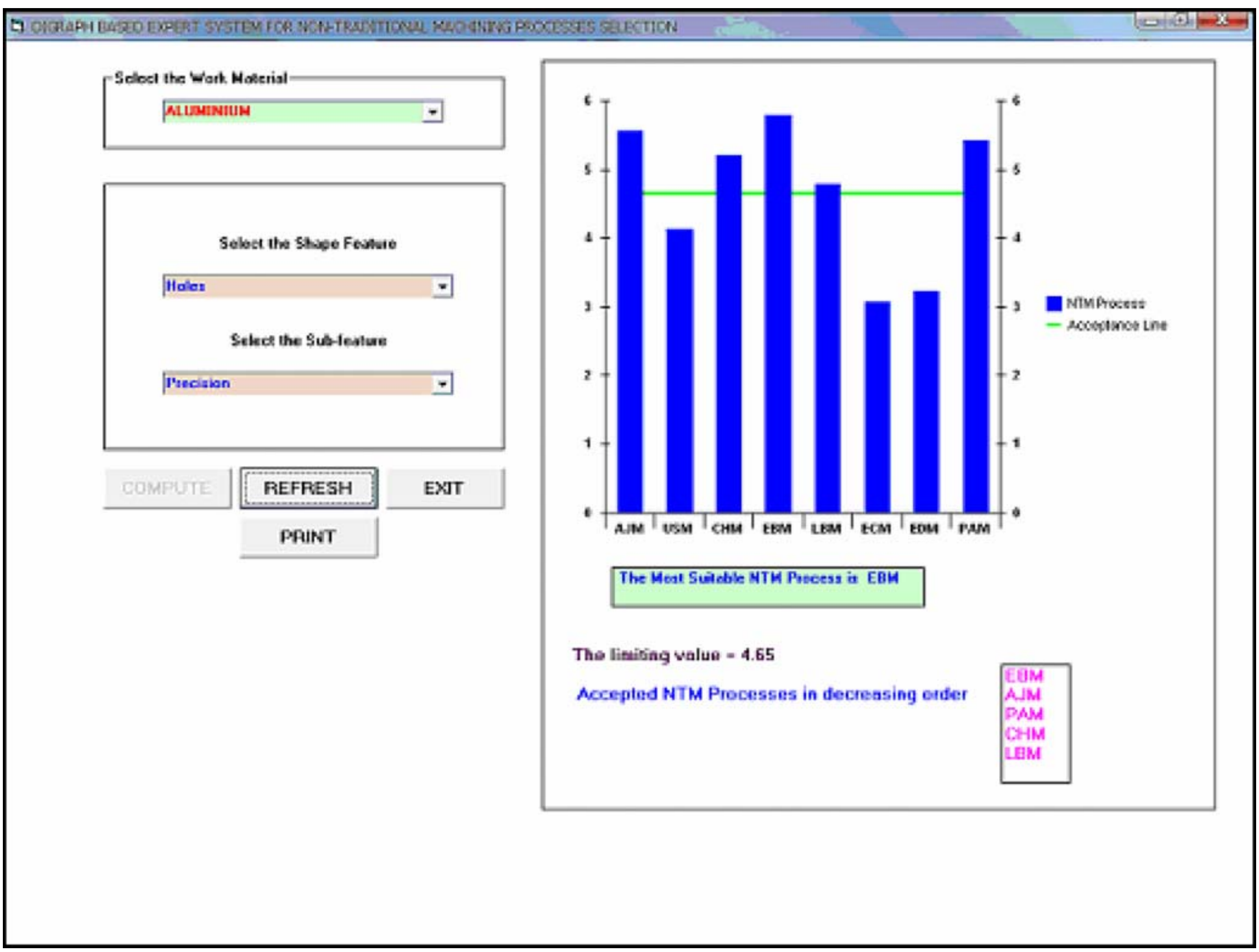

Fig. 3 Graphical output for example 1

Table 7 Normalised NTM process selection attributes for example 2

NTM process	TSF	MRR (mm^3/min)	PR	C	F	M
AJM	0.4000	0.000010	0.9091	1.0000	0.2000	0.8000
USM	1.0000	0.004000	0.0833	0.5000	0.2000	0.8000
CHM	0.3333	0.000200	0.5000	0.3333	0.2000	0.8000
EBM	0.4000	0.000020	1.0000	0.2500	0.8000	0.8000
LBM	0.5000	0.000001	0.1428	0.3333	0.8000	0.8000
ECM	0.3333	0.020000	0.0020	0.2000	1.0000	0.8000
EDM	0.2857	0.010670	0.0741	0.3333	0.2000	1.0000
PAM	0.2000	1.000000	0.0040	1.0000	1.0000	0.8000

(e) Refractories
(f) Plastics
(g) Ceramics
(h) Glass

Again, the following shape features are considered that can be generated by the available NTM processes:

(a) Holes
 1. Precision
 2. Standard with L/D ratio <20
 3. Standard with L/D ratio >20

(b) Through cavities
 1. Precision
 2. Standard

(c) Surfacing
 1. Double contouring
 2. Surface of revolution

(d) Through cutting
 1. Shallow
 2. Deep

In order to select the most appropriate NTM process for a given material and shape feature combination, Eq. 3, i.e. the permanent of the matrix, is to be solved, substituting the values of A_i and a_{ij}. The NTM process having the highest permanent of matrix value is the best choice for the given application.

6 Inputs and outputs of the expert system

In this paper, an expert system is designed and developed in Visual Basic 6.0 at the front end, with Microsoft Office Excel 2003 at the back to store the database, while utilising SP6 for including Microsoft Chart Control 2.0 to display the graphical outputs. The initial input window of the developed expert system is exhibited in Fig. 2. The graphical user interface of the expert system helps the user to avoid all the multifarious calculations related to normalisation and permanent values of the matrices. The expert system displays those permanent values of the matrices while selecting the most suitable NTM process for a given application. Its home window has four functional buttons, i.e. 'COMPUTE', 'PRINT', 'REFRESH' and 'EXIT' in the left and a picture box in the right to portray the outputs graphically. This window also has the options for selecting the work material type and shape feature to be generated from the pop-down menus. After choosing the work material and shape feature, pressing of the 'COMPUTE' button calculates the permanent values of the matrices related to different NTM processes and lists those NTM processes that are suitable for the given combination. The hardcopy of the computed results can be obtained by clicking the 'PRINT' button. The 'REFRESH' button allows the user to input a new set of work material and shape feature combination after getting the results from the previous analysis. The 'EXIT' button closes the home window of the expert system, returning back to the Windows operating system. All the necessary error trapping messages are provided in the expert system for ease of the users.

6.1 Example 1

In this example, aluminium is chosen as the work material and precision holes are to be generated on it. At first, to select the most suitable NTM process for machining of precision holes on aluminium, the capabilities of different NTM processes with respect to six attributes are considered and compared [2]. Among these NTM process selection attributes, TSF, MRR and PR are based on absolute scales, whereas C, F and M are assigned with rank judgment scales. MRR, F and M are the beneficial attributes, where higher values are desirable. On the other hand, TSF, PR and C are non-beneficial attributes, and for these attributes, lower values are desirable. The quantitative values of the NTM process

Table 8 Permanent values for example 2

NTM process	Permanent of matrix	Average
AJM	5.5608	4.8015
USM	4.4425	
CHM	3.8728	
EBM	5.7866	
LBM	4.4879	
ECM	4.0360	
EDM	3.4398	
PAM	6.7852	

selection attributes are given in Table 3. These values are purely based on the experimental results and expert opinions [1, 2]. Table 4 exhibits the normalised values of these attributes for different NTM processes. Depending on the capability of a particular NTM process to machine a desired shape feature on a given work material, the entries of the last two columns of Table 3 usually need to be changed. The developed expert system automatically takes care of those values from its KB and constructs the final NTM process selection matrix from which the permanent value related to each NTM process is computed. Table 5 gives the permanent values of the matrices for different NTM processes.

When the user completes inputting the work material type and shape feature to be machined on that material, he/she needs to press the 'COMPUTE' button to obtain the computational results and related graphical outputs. In this example, the most suitable NTM process is EBM. The expert system also lists the other acceptable NTM processes (AJM, PAM, CHM and LBM) in descending order of preference. The selection of the acceptable NTM processes for the given situation is entirely based on the calculation of the permanent values of matrices associated with the NTM processes. The average permanent value of the matrices is calculated as 4.6450. The NTM processes with permanent of matrix value greater than the average are considered to be acceptable for machining of precision holes on aluminium. The graphical output from the expert system is exhibited in Fig. 3.

6.2 Example 2

Here, a deep through cutting operation is to be performed on titanium. The quantitative values of the NTM process

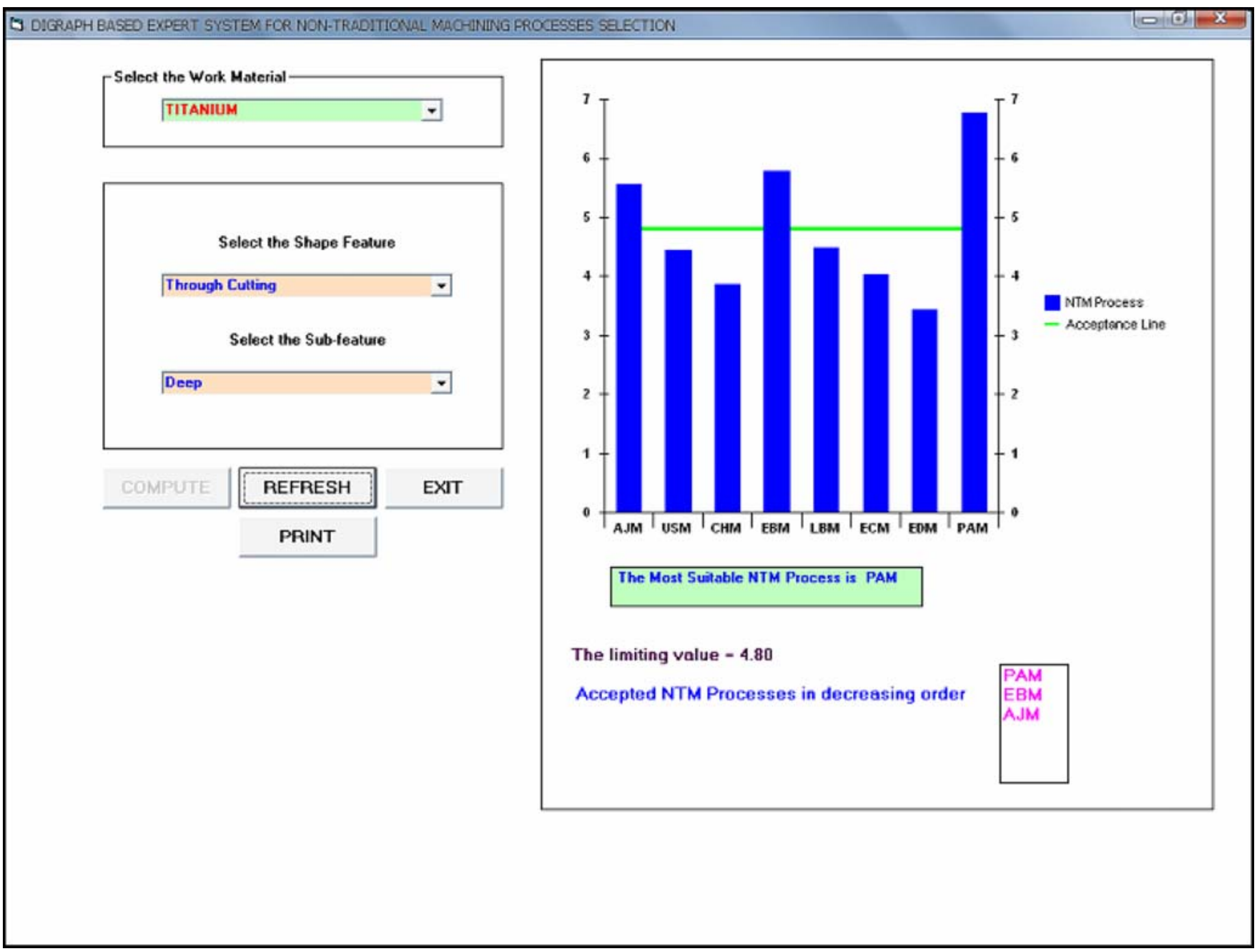

Fig. 4 Output for example 2

selection attributes and their normalised values are given in Tables 6 and 7, respectively. Based on the computed permanent of matrix values for different NTM processes, the expert system selects PAM as the most appropriate NTM process. Electron beam and AJM processes can also generate deep through cut on titanium, but having lower priorities than PAM. Table 8 gives the values of the permanent of matrices based on which the NTM process selection decision is made. Figure 4 shows the graphical output of the expert system.

6.3 Example 3

Yurdakul and Cogun [5] suggested a multi-attribute NTM process selection approach using TOPSIS and AHP methods. They considered the generation of cylindrical through holes on ceramic (non-conductive). The hole diameter and slenderness ratio (L/D) were 0.64 mm and 5.7, respectively. Based on their proposed methodology, the ranking of the NTM processes was USM–LBM–EBM–CHM–AJM. The same work material and shape feature combination is taken here as another example for the developed expert system. The graphical output, as shown in Fig. 5, ranks the accepted NTM processes as USM–AJM–EBM.

6.4 Example 4

Chakraborty and Dey [6] considered the generation of surface of revolution feature on aluminium while adopting their AHP-based expert system approach for NTM process selection and observed that ECM and PAM were the most acceptable NTM processes. The same work material and shape feature combination is given as input in this expert system. Figure 6 displays the graphical output where ECM, PAM, LBM and USM processes are ranked according to descending order of preference for machining of standard

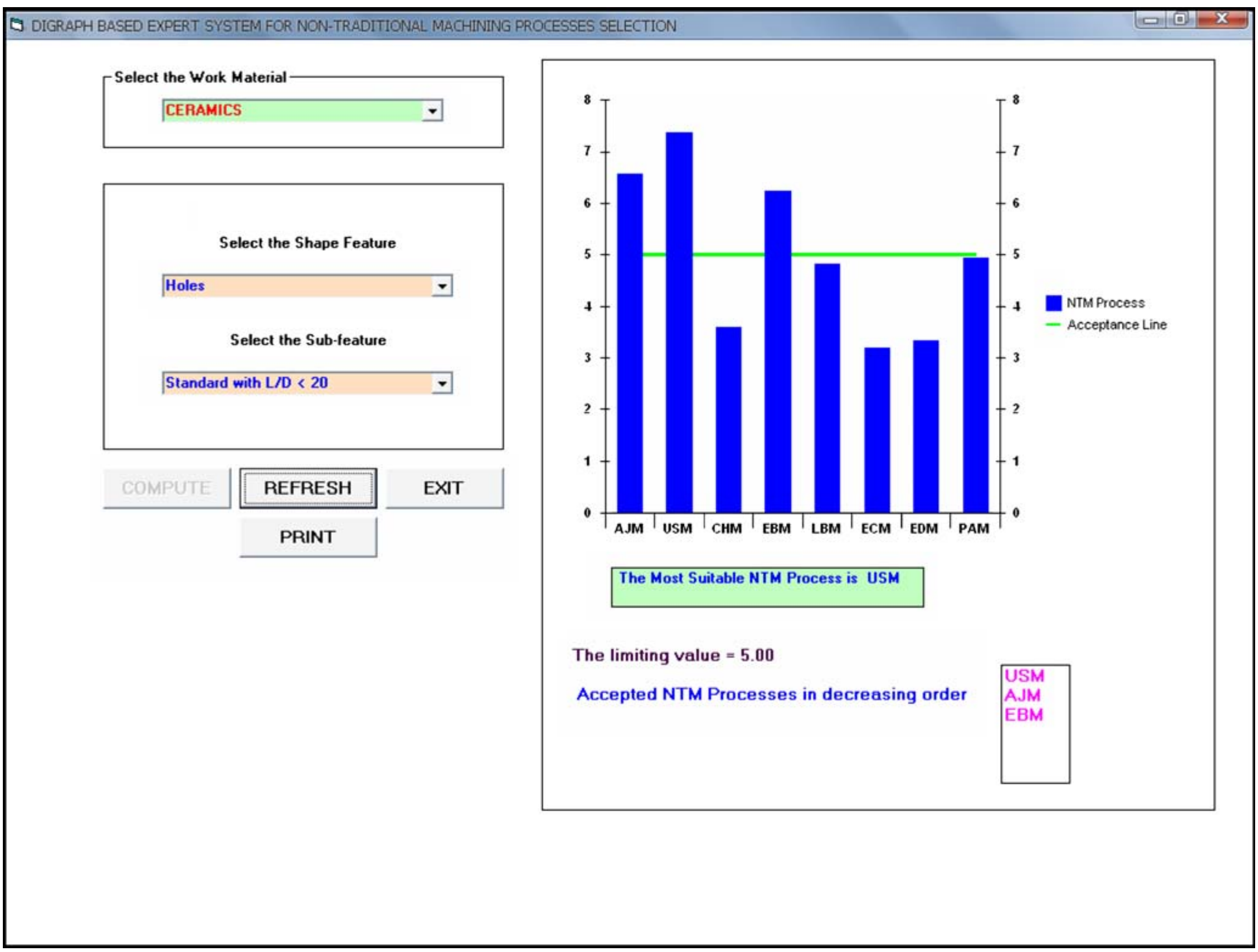

Fig. 5 Graphical output for example 3

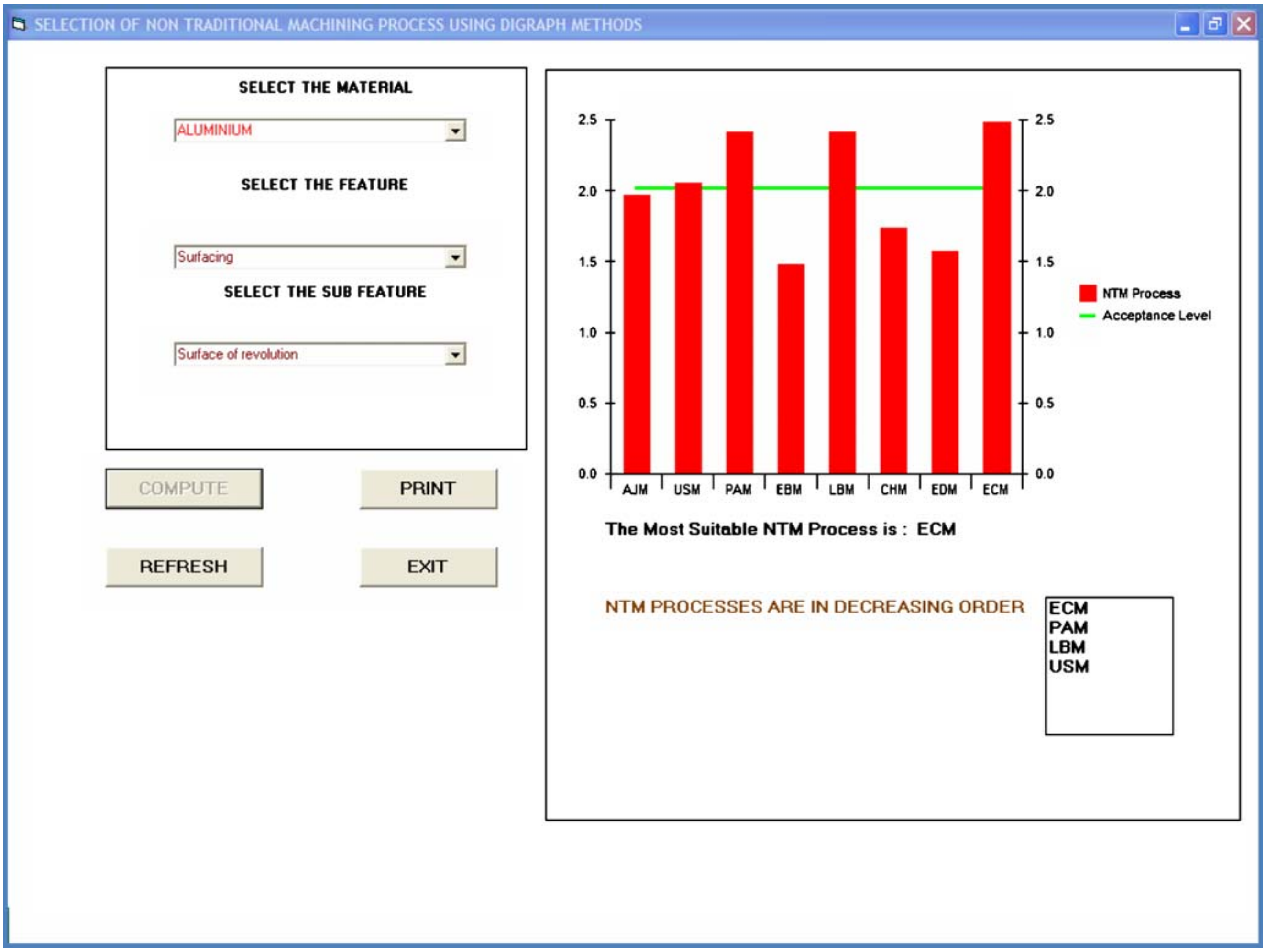

Fig. 6 Graphical output for example 4

through holes on titanium. It is observed that all the results obtained from the expert system are more or less the same as those derived by the past researchers, which show the greater acceptability and applicability of the developed expert system while selecting the NTM processes in a real-time manufacturing environment.

7 Conclusions

A methodology based on the development of a digraph-based expert system is proposed which helps in selecting the most suitable NTM process from a large number of available alternative NTM processes for machining of a shape feature on a given work material. The proposed system identifies and considers different NTM process selection attributes and their interrelations for a given NTM process selection problem. It can simultaneously take into account any number of quantitative and qualitative NTM process selection attributes and offer a more objective and simple NTM process selection approach. The comparative study between the alternative NTM processes aids in developing and deploying the available technologies by focusing into the process characteristics that are not present in the considered NTM processes in terms of their capabilities to machine a specific shape feature on a given work material. Another advantage of this expert system is that it does not require having any in-depth technological knowledge regarding the applicability of the NTM processes. Moreover, it relieves the user from committing any error while taking the decision regarding the selection of the most suitable NTM process for a given machining application. This expert system can be employed as a benchmark to select the NTM processes for different machining applications. It can be made more dynamic and versatile by including all the NTM processes, shape features and materials yet to come in the near future.

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