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INTELLIGENT METHODOLOGY FOR OPTIMAL SELECTION OF NON-TRADITIONAL MACHINING PROCESSES

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ABSTRACT

Manufacture of a product in a desired shape and size with specific characteristics and properties depends not only on the design of the product but also on the selection of the appropriate manufacturing process(es) that requires knowledge about various available alternatives. This paper presents a software for selecting the optimal non-traditional machining process(es) from twenty one processes. It has been developed using MATLAB, version (V7.8) release (R2009a), as programming language with the help of graphical user interface (GUI), visual aids, and fuzzy logic toolboxes. The selection procedures are based on elimination and ranking technique, considering important attributes such as workpiece material and shape generation requirements, NTMPs operational capabilities, and NTMPs economical and environmental aspects. Cases of partial suitability of a particular process with respect to the operational requirements and providing unequal importance to them are considered, which increase the accuracy of the proposed software than previous works. An industrial case study, taken from Luxcelis Company, is implemented on the software for verification. Luxcelis Company uses laser machining system for the formation of cooling holes in high pressure turbine blades for aerospace turbine engines.

KEY WORDS

Non-Traditional Machining, Material, Shape, Operational Capabilities, Economical Aspects, Environmental Aspects, Fuzzy Logic, Membership Function, IF-THEN Rules, Sugeno Inference System, and Suitability Index.

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ACRONYMS

AFM	:	Abrasive Flow Machining
AHP	:	Analytic Hierarchy Process
AJM	:	Abrasive Jet Machining
AWJM	:	Abrasive Water Jet Machining
CAPP	:	Computer Aided Process Planning
CHM	:	Chemical Milling
EBM	:	Electron Beam Machining
ECG	:	Electrochemical Grinding
ECH	:	Electrochemical Honing
ECM	:	Electrochemical Machining
EDG	:	Electrical Discharge Grinding
EDM	:	Electrical Discharge Machining
EDMM	:	Electrical Discharge Machining Milling
ESD	:	Electro stream Drilling
GUI	:	Graphical User Interface
IBM	:	Ion Beam Machining
LBM	:	Laser Beam Machining
MAF	:	Magnetic Abrasive Finishing
MRR	:	Material Removal Rate
PAM	:	Plasma Arc Machining
PCM	:	Photochemical Milling
QFD	:	Quality Function Deployment
RUM	:	Rotary Ultrasonic Machining
STEM	:	Shaped Tube Electrochemical Machining
TOPSIS	:	Technique for Order Preference by Similarity to Ideal Solution
USM	:	Ultrasonic Machining
WEDM	:	Wire Electrical Discharge Machining
WJM	:	Water Jet Machining

INDRODUCTION

Ever-growing demand for better, durable, and reliable product performance has brought about a materials revolution, thus greatly expanding the families of some alloys (i.e. super-alloys) and that of the non-metallic materials namely polymers, ceramics, and composites. These materials can be engineered to have a wide variety of unique properties and characteristics like very high strength and stiffness at elevated temperatures, extreme hardness and brittleness, high strength to weight ratio, very good oxidation and corrosion resistance, chemical inertness, etc., making them commercially attractive [1-7].

In this respect, conventional machining and shaping processes result in high costs and even degradation of some useful properties. These materials development related factors along with the requirements like high precision machining of complex and complicated shapes and/or sizes, machining at micro- or nano-levels, machining of inaccessible areas, surface integrity, tool wear considerations, economic return, burr free machining, low applied forces, etc., have contributed significantly in the development of various non-traditional machining processes (NTMPs). Most of these processes are associated with relatively high initial investment or capital cost, power consumption and operating cost, tooling and fixture cost, and maintenance cost. However they are non-versatile from the application point of view as a particular NTMP that is found suitable under specific condition may not be equally effective and efficient under different conditions. Therefore, effective, efficient, and economic utilization of potential and capabilities of NTMPs necessitate careful selection of an appropriate process [1-7].

In this regard, experts often make correct decision regarding process selection, but transfer of their experience and expertise is a time consuming process and sometimes almost infeasible, on the other hand, industrial applications of NTMPs are increasing constantly. In this context, collection, computerization, and integration of the widely scattered knowledge, experience, expertise, and skills related to the selection of NTMPs, and subsequently implementation in the form of an integrated, automated, intelligent, interactive, and rational CAPP system can help different users of NTMPs, particularly to the mid-level manufacturing engineers working at shop-floor and lacking in-depth technical knowledge.

Since 1993 there were many NTMPs selection methods and procedures developed, e.g. Cogun [8, 9] proposed a computer-aided system for selection of NTMPs considering attributes such as work material, surface roughness, tolerance, corner radii, width of cut, hole diameter, aspect ratio, and taper. Mestry [10] proposed a software tool taking in consideration the machining time or MRR capability in the selection of conventional machining, advanced machining, advanced finishing, and cutting processes. Yurdakul and Cogun [11] proposed a multi-attribute selection procedure to determine suitable NTMPs for a given application requirements by using AHP and TOPSIS, considering attributes such as work material, shape application, process capability, and machining cost. Chakraborty and Dey [12, 13] proposed a methodology for selecting the optimal NTMP by using AHP or QFD, considering attributes such as material application, shape application, process capability, process economy, and environmental effect. Edison et. al. [14] proposed a web-based knowledge base system for identifying the most appropriate NTMP based on elimination and ranking technique, considering attributes such as material type, shape applications, process capabilities, and process economy. Chakladar et. al. [15] proposed a digraph-based approach to select the appropriate NTMP, considering attributes such as tolerance and surface finish, MRR, power requirement, cost, shape feature, and work material type. El-Safi [16] proposed a thesis that covers NTMPs selection based on elimination and ranking technique using AHP, considering attributes such as material to be machined, machining operations, quality aspects, economical aspects, and environmental aspects.

Therefore, the aim of this work is to aid an engineer in making the right decisions regarding process selection and manufacturability evaluation at the design stage itself, taking into account important attributes such as workpiece material and shape generation requirements, NTMPs operational capabilities, and NTMPs economical and environmental aspects. The advantages of the proposed software over previous works:

- It considers twenty one NTMPs.
- It considers more than two hundred workpiece materials.

- It considers more than thirty machining operation types.
- It considers more than fifteen important NTMPs operational capabilities.
- Cases of partial suitability of a particular process with respect to the operational requirements and providing unequal importance to them are considered, which increase the proposed software accuracy.

FUZZY LOGIC

Fuzzy logic was introduced by Lotfi Zadeh [17] in 1965, while contemplating how computers could be programmed for handwriting recognition.

Fuzzy Logic Toolbox software [18] is a collection of functions built on the MATLAB technical computing environment. Two types of inference systems can be implemented in the toolbox (i.e. Mamdani-type and Sugeno-type). *Sugeno-type* is implemented in this work as it uses a singleton as the membership function of the rule consequent. The final output of the system is the weighted average of all rule outputs, computed as:

$$Final\ Output = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \qquad (1)$$

where N is the number of rules. The output level z_i of each rule is weighted by the firing strength w_i of the rule.

NTMPs SELECTION PROCEDURES

Figure 1 depicts the concept of the proposed selection and ranking methodology of NTMPs. Twenty one NTMPs have been considered (i.e. USM, RUM, AJM, WJM, AWJM, AFM, MAF, CHM, PCM, ECM, ESD, STEM, ECG, ECH, EDM, EDG, WEDM, EBM, LBM, PAM, and IBM). The proposed methodology uses a combination of elimination and ranking strategy as follows:

First Level: This level employs an elimination strategy based on the required workpiece material. Table 1 shows a part of material based reclassification of NTMPs. By using this reclassification, non-applicable NTMPs to the work material are eliminated from the initial list of NTMPs.

Second Level: This level also implements an elimination strategy based on the required shape. Table 2 shows a part of shape generation capabilities based reclassification of NTMPs. By using this reclassification, non-applicable NTMPs are eliminated from the initial list. NTMPs common to the short-lists of first level and second level are retained for the next level.

Third Level: This level employs a ranking strategy by using Sugeno fuzzy logic inference system. A suitability index based on the operational requirements of the desired application is computed for the output NTMPs. Equation 1 is used to compute this suitability index using the database of their finishing and machining capabilities. Table 3 shows a part of this database. Various operational capabilities of NTMPs can be categorized as finishing capabilities and machining capabilities. Finishing capabilities include surface roughness, tolerance, surface damage depth, overcut, and corner radii. Machining capabilities are specific to a particular machining operation and include the capabilities like drilling capabilities (i.e. hole diameter, hole depth, aspect ratio, hole taper, hole axis inclination, and number of holes that can be drilled simultaneously in the same run), and cutting capabilities (i.e. width of cut, depth of cut, cut taper, and MRR).

Most of the process capabilities are generally expressed in numerical ranges, which often can be split as most common range [a_{ij}, b_{ij}] and attainable value [c_{ij}]. Therefore, fuzzy sets are more suitable tools for representation and comparison of such type of process capabilities using trapezoidal membership function as illustrated in Fig. 2. In such representation, any value within the most common range of a process capability is assigned a membership value of 1, while any value within the attainable range, [c_{ij}, a_{ij}] or [b_{ij}, c_{ij}], is assigned a membership value between 0 and 1. It signifies the fact that with moving away from the most common range of process capability the chances of meeting the requirement reduces.

The process capabilities can be classified as larger-the-better and smaller-the-better type according to their nature. Hole depth, aspect ratio, number of holes that can be drilled simultaneously in the same run, depth of cut, and MRR are of larger-the-better type as the optimality of these capabilities is to be maximum, while the remaining process capabilities are of smaller-the-better type as the optimality of these capabilities is to be minimum.

Fourth Level: This level employs a ranking strategy based on NTMPs economical aspects (i.e. capital or initial investment cost, tooling and fixture cost, power consumption cost, and tool consumption cost), and environmental aspects (i.e. safety, toxicity, and contamination of machining medium).

Information available about these aspects is qualitative in nature and difficult to quantify. It is described in terms of linguistic variables like very low, low, medium, high and very high for capital, tooling, and power consumption costs, no tool wear, medium tool wear, and high tool wear for tool consumption index, and no problem, normal problem, and critical problem for different environmental aspects. Table 4 shows a part of NTMPs economical and environmental aspects database where each of NTMP economical and environmental suitability index are computed by summing up the numerical values assigned to its different aspects. The output suitability indices are added to operational suitability index for each NTMP to make the final ranking to get the optimal NTMP(s).

CASE STUDY

Luxcelis Company [19] provides laser machining system for the formation of cooling holes in high pressure turbine blades for aerospace turbine engines. The machining requirements are:

- *Workpiece material requirements:* Inconel.
- *Shape generation requirements:* Inclined drilling.
- *Operational requirements:*

- Surface *roughness:* 0.4 µmRa.
- *Hole tolerance:* ±3.5 µm.
- *Hole diameter:* 0.07 mm.
- *Hole depth:* 2.9 mm.
- *Hole inclination angle with respect to workpiece surface:* 20^{o}

The implementation of the proposed methodology is as follows:

First Step: Select workpiece material. Inconel material is Ni-based super alloy and is selected from non-ferrous alloys.

Second Step: Select machining operation type. Inclined drilling is selected from one-dimensional machining operation.

After selecting the required workpiece material and machining operation type, click on the NTMPs button to implement the elimination strategy and get the acceptable NTMPs as shown in Fig. 3. AJM, WJM, ESD, STEM, EDM, EBM, and LBM are considered as the acceptable NTMPs.

Third Step: Click on the operational capability fuzzy logic button to implement Sugeno fuzzy logic inference system on the acceptable NTMPs. It consists of the following steps:

1. Add the required input variables (i.e. surface roughness, tolerance, hole diameter, hole depth, and hole inclination angle), and output variable (i.e. suitability index).
2. For each input variable enter the trapezoidal membership function for each NTMP, and for the output variable enter two constant membership functions of values 0 and 1.
3. For each NTMP enter the IF-THEN rules, which state that if the operational requirements lie within NTMP operational capabilities then the output suitability index will be 1, but if the requirements did not lie within NTMP capabilities then the output suitability index will be 0.
4. Enter the requirements in a form of a vector in which each element in this vector corresponds to each NTMP operational capability. Equation 1 is used to compute the final output, which is the weighted average of all rule outputs. Table 5 shows LBM suitability index computations.

Fourth Step: Each NTMP economical and environmental suitability index are added to each NTMP operational capability suitability index by clicking on final ranking button. Also a bar chart is displayed showing the overall ranking of the optimal NTMPs as shown in Fig. 4.

RESULTS AND DISCUSSIONS

The result shows that LBM is the optimal NTMP as it achieves the highest priority percentage due to the following reasons:

- Inconel can be machined easily by LBM.
- Drilling inclined through hole of diameter less than 1 with aspect ratio more than 20 can be achieved easily by LBM.

- All given requirements lie within the common range of LBM operational capabilities, which achieve suitability index equal to 1.
- LBM achieves the highest environmental suitability index.

CONCLUSION

This work proposes software for selecting the optimal NTMPs from twenty one processes, considering important attributes such as work material and shape generation requirements, NTMPs operational capabilities, and NTMPs economical and environmental aspects.

This software is a great help for the designer in identifying possible alternatives early in the design process, do to ease of manufacturing, saving time, effort, and cost, particularly for users that not have expertise in NTMPs.

Fuzzy Logic Toolbox software is implemented on NTMPs operational capabilities as it relies heavily on GUI tools, so it is flexible and easy to understand. Unequal importance or weightage can be applied easily to all or some of the given operational capabilities. Also cases of partial suitability of a particular process with respect to the given operational capabilities can be considered for more flexibility and accuracy.

The obtained results from implementing the proposed software to the given case study are the same as those derived by its company, which proves the validity, acceptability, and applicability while selecting the optimal NTMPs in a real time manufacturing environment.

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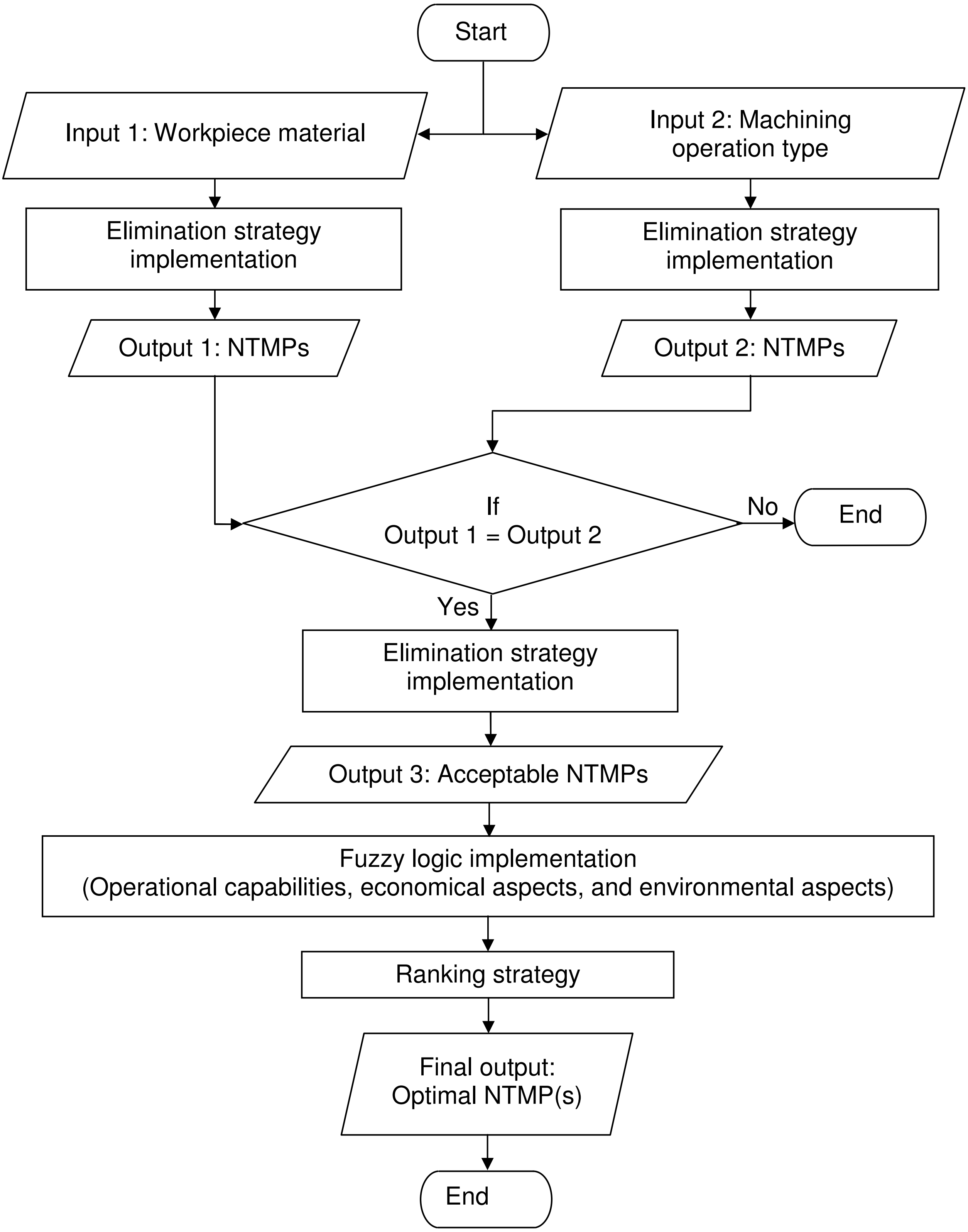

Fig.1. Flow chart depicting the concept of the proposed methodology.

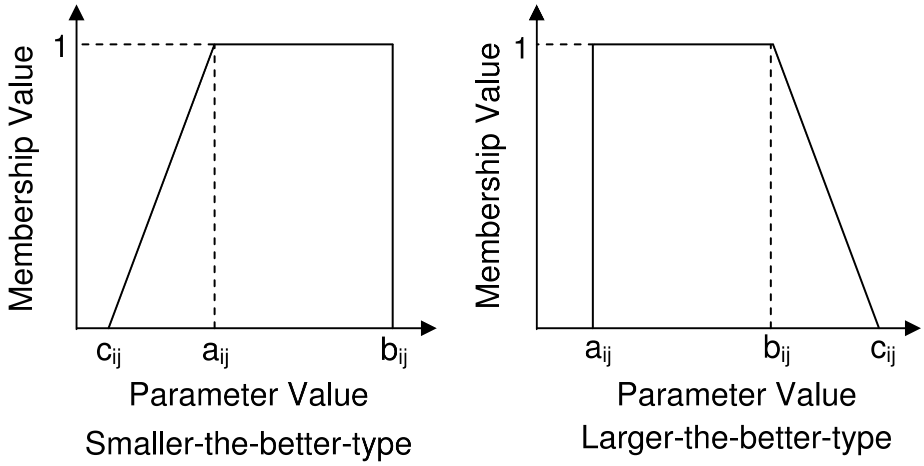

Fig.2. Process capabilities membership functions.

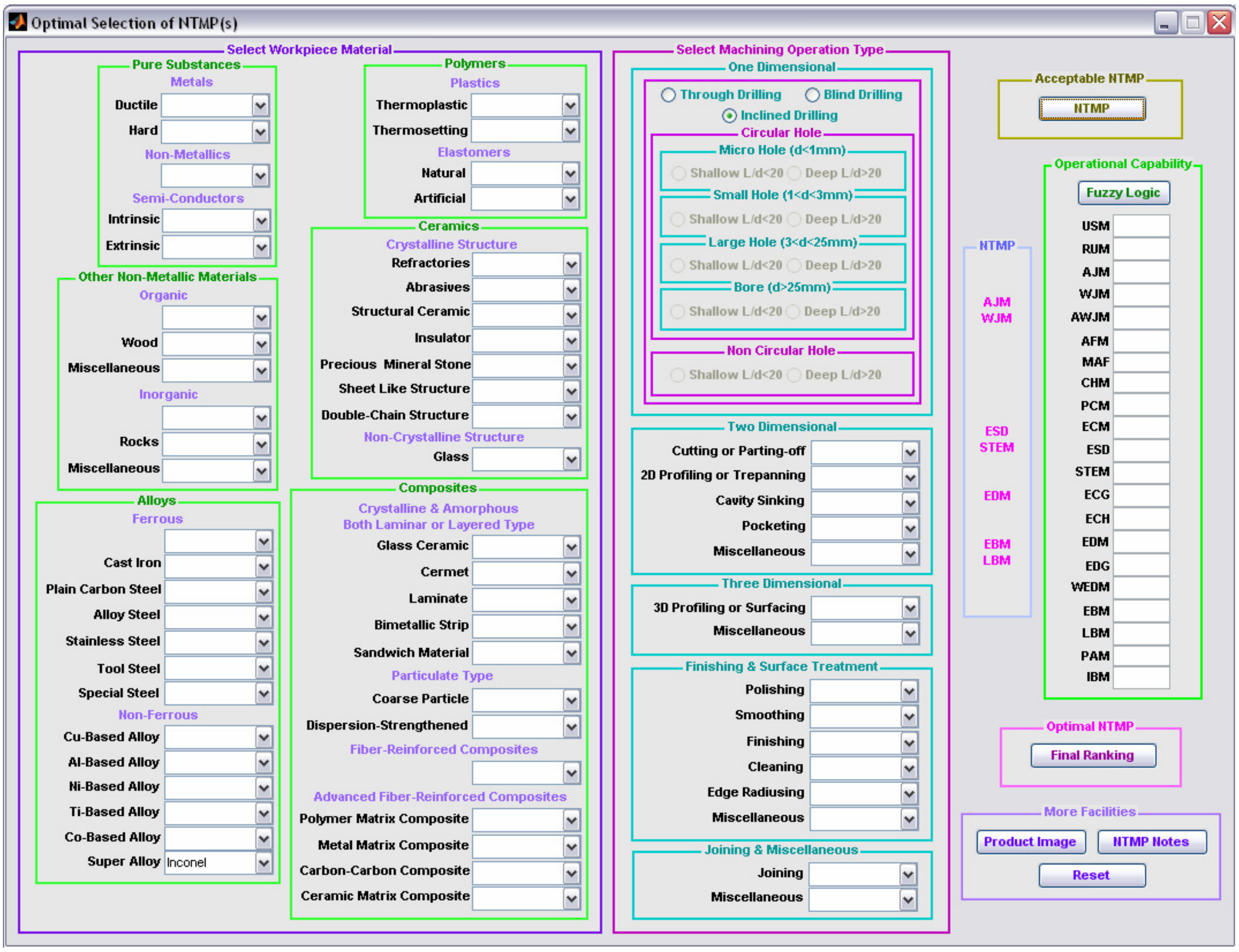

Fig.3. Acceptable NTMPs.

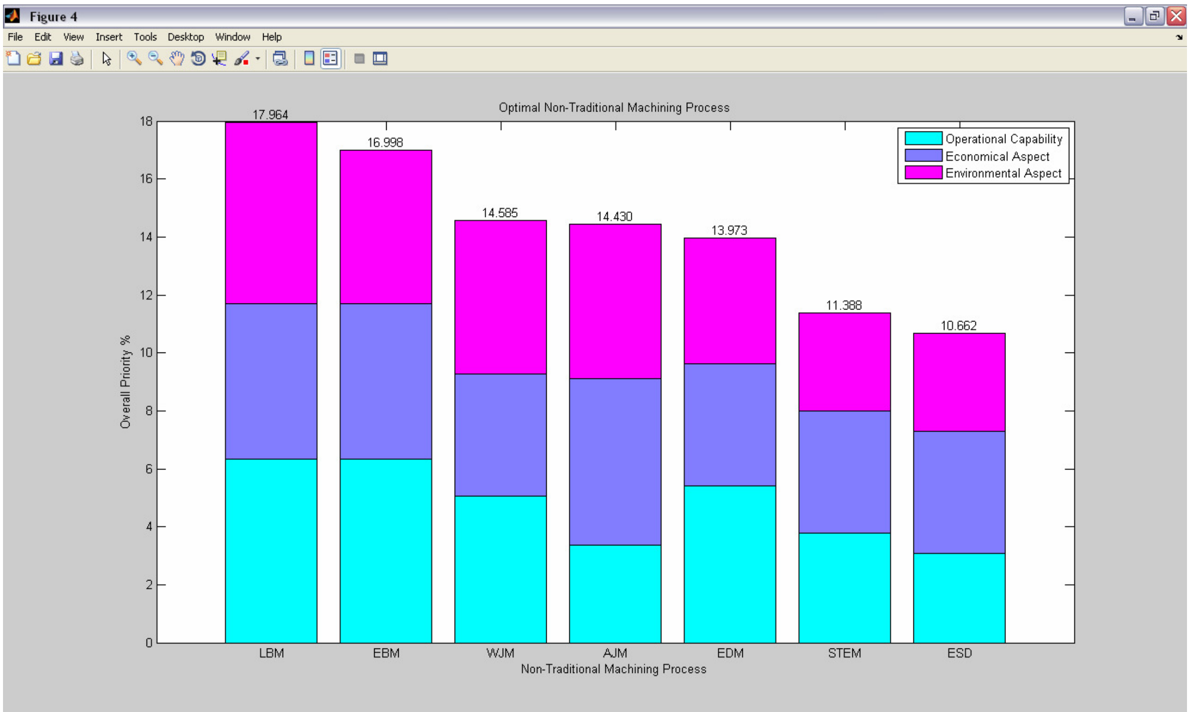

Fig.4. The optimal NTMPs.

Table 1. A part of material based reclassification of NTMPs.

Basic Category of Workpiece Material	Sub-Category of Workpiece Material	Sub-Sub-Category of Workpiece Material	Examples	Applicable NTMPs
Alloys	Non-ferrous alloys	Cu-based alloys	Brass, Bronze, Constantan, Cupronickel	USM, RUM, AJM, WJM, AWJM, AFM, MAF, CHM, PCM, ECM, ESD, STEM, ECG, ECH, EDM, EDG, WEDM, EBM, LBM, PAM
		Al-based alloys	Duralumin, Hindalium, Magnalium	
		Ni-based alloys	Monel, Nichrome	

Table 2. A part of shape generation capabilities based reclassification of NTMPs.

Basic Category of Machining Operation	Name of Machining Operation	Applicable NTMPs
Joining and miscellaneous operations	Chemical leaching	CHM
	Cable-stripping	AJM, WJM
	Grinding wheels Redressing	AWJM, LBM
	Tool or cutter sharpening	USM, ECG, IBM

Table 3. A part of various NTMPs operational capabilities.

Operational Capability	**USM**	**AJM**	**WJM**	**AWJM**	**AFM**
Surface roughness (µmRa)					
Attainable value	0.1	0.1	0.1	1.25	0.025
Common range	0.2-1.6	0.2-1.5	0.3-6.4	1.25-6.4	0.07-1.9

Table 4. A part of various NTMPs economical and environmental aspects.

<table>
<tr><th colspan="6">Economical Aspect Type</th><th>USM</th></tr>
<tr><td colspan="6">Capital or initial investment cost</td><td>L</td></tr>
<tr><td colspan="6">Tooling and fixtures cost</td><td>L</td></tr>
<tr><td colspan="6">Power consumption cost based on specific power consumption</td><td>M</td></tr>
<tr><td colspan="6">Tool consumption cost based on tool or nozzle wear rate</td><td>MTW</td></tr>
<tr><td colspan="6">Economical Suitability Index (Maximum value = 4)</td><td>2.8</td></tr>
<tr><th colspan="6">Environmental Aspect Type</th><th>ECM</th></tr>
<tr><td colspan="6">Safety</td><td>NRP</td></tr>
<tr><td colspan="6">Toxicity</td><td>NP</td></tr>
<tr><td colspan="6">Contamination of machining medium</td><td>CP</td></tr>
<tr><td colspan="6">Environmental Suitability Index (Maximum value = 3)</td><td>1.8</td></tr>
<tr><th colspan="7">Abbreviations and numerical values assigned to them</th></tr>
<tr><td>VL: Very Low</td><td>1</td><td rowspan="2">NTW: No Tool Wear</td><td rowspan="2">1</td><td rowspan="2">NP: No Problem</td><td rowspan="2" colspan="2">1</td></tr>
<tr><td>L: Low</td><td>0.8</td></tr>
<tr><td>M: Medium</td><td>0.6</td><td>MTW: Medium Tool Wear</td><td>0.6</td><td>NRP: Normal Problem</td><td colspan="2">0.6</td></tr>
<tr><td>H: High</td><td>0.4</td><td rowspan="2">HTW: High Tool Wear</td><td rowspan="2">0.2</td><td rowspan="2">CP: Critical Problem</td><td rowspan="2" colspan="2">0.2</td></tr>
<tr><td>VH: Very High</td><td>0.2</td></tr>
</table>

Table 5. LBM operational capabilities suitability index computations.

Operational Requirements	**Desired Value**	**Rule Weightage**	**LBM Capabilities**		**Level Priority**
Surface roughness (µmRa)	0.4	$w_1 = 1$	Attainable value	0.2	$z_1 = 1$
			Common range	0.4-6.3	
Hole tolerance (±µm)	3.5	$w_2 = 1$	Attainable value	0.1	$z_2 = 1$
			Common range	0.5-170	
Hole diameter (mm)	0.07	$w_3 = 1$	Attainable value	0.002	$z_3 = 1$
			Common range	0.01-3.4	
Hole depth (mm)	2.9	$w_4 = 1$	Common range	0.1-50	$z_4 = 1$
			Attainable value	75	
Hole inclination angle	20^o	$w_5 = 1$	Attainable value	6^o	$z_5 = 1$
			Common range	20^o-90^o	

$$LBM\ Suitability\ Index = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} = \frac{(1\times 1)+(1\times 1)+(1\times 1)+(1\times 1)+(1\times 1)}{(1+1+1+1+1)} = 1$$