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NON-CONVENTIONAL MACHINING PROCESSES SELECTION USING MULTI-OBJECTIVE OPTIMIZATION ON THE BASIS OF RATIO ANALYSIS METHOD

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Abstract

The role of non-conventional machining processes (NCMPs) in today's manufacturing environment has been well acknowledged. For effective utilization of the capabilities and advantages of different NCMPs, selection of the most appropriate NCMP for a given machining application requires consideration of different conflicting criteria. The right choice of the NCMP is critical to the success and competitiveness of the company. As the NCMP selection problem involves consideration of different conflicting criteria, of different relative importance, the multi-criteria decision making (MCDM) methods are very useful in systematical selection of the most appropriate NCMP. This paper presents the application of a recent MCDM method, i.e., the multi-objective optimization on the basis of ratio analysis (MOORA) method to solve NCMP selection which has been defined considering different performance criteria of four most widely used NCMPs. In order to determine the relative significance of considered quality criteria a pair-wise comparison matrix of the analytic hierarchy process was used. The results obtained using the MOORA method showed perfect correlation with those obtained by the technique for order preference by similarity to ideal solution (TOPSIS) method which proves the applicability and potentiality of this MCDM method for solving complex NCMP selection problems.

Keywords: Non-conventional machining processes, Multi-criteria decision making, Selection, MOORA method.

1. Introduction

In today's industry, a number of non-conventional machining processes (NCMPs) are increasingly being used for processing of different engineering materials

Nomenclatures

b_{ij}	Comparative importance of criterion i with respect to criterion j
g	Number of criteria to be maximized
m	Number of alternatives
n	Number of criteria
R_a	*Average surface roughness, µm*
r	Number of criteria to be minimized
w_j	Weight of the j-th criterion
x_{ij}	Performance measure of i-th alternative with respect to j-th criterion
x_{ij}^*	Normalized performance measure of i-th alternative with respect to j-th criterion.
y_i	Alternative assessment values

Abbreviations

AJM	Abrasive-jet machining
AWJM	Abrasive water jet machining
CHM	Chemical machining
EBM	Electron beam machining
ECM	Electrochemical machining
EDM	Electro-discharge machining
GM	Geometric mean
LBM	Laser beam machining
MCDM	Multi-criteria decision making
MOORA	Multi-objective optimization on the basis of ratio analysis
NCMPs	Non-conventional machining processes
PAM	Plasma-arc machining
TOPSIS	Technique for order preference by similarity to ideal solution
USM	Ultrasonic machining
WEDM	Wire electrical discharge machining
WJM	Water jet machining

especially advanced materials having improved technological and mechanical properties. Laser beam machining (LBM), abrasive water jet machining (AWJM), electrical discharge machining (EDM) and plasma arc machining (PAM) are particularly used in industry for materials processing. Each of these NCMP is very complex machining process having its own unique characteristics, prerequisites and advantages.

For many firms, having some core competency is necessary for making strategic decisions like technology selection decision. Since some of the consequences of technology selection occur at long-run, firms' survival at long term depends heavily on their ability to exploit some core competencies [1]. Making right decision is a basis for achieving high competitiveness on the global market through increase in productivity, product quality and flexibility. As the price of machine tools for NCMPs is very high, inadequate selection of the most appropriate NCMP has long-term consequences on the business of the entire company. However, selection of the most appropriate NCMP is a challenging task for decision makers [2] and moreover often a time consuming task [3].

From the literature (Table 1) it has been observed that different multi-criteria decision making (MCDM) methods have been applied for solving NCMP selection problems. MCDM is concerned with those situations where a decision maker has to rank a set of competitive alternatives and select the best alternative while considering a set of conflicting criteria [4]. In order to evaluate the overall performance of the competitive alternatives, the primary objective of an MCDM method is to identify the relevant selection problem criteria, assess the alternative's information relating to those criteria and develop methodologies for determining the relative significance of each criterion.

For solving NCMP selection problems, analytic hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods were applied [5, 6]. Digraph-based approach was discussed in [2]. Application of analytic network process (ANP) method was proposed in [7]. Later on, the use of data envelopment analysis (DEA) method was proposed [8]. Application of preference ranking organization method for enrichment evaluation (PROMETHEE) and geometrical analysis for interactive aid (GAIA) method was discussed in [9]. Recently, the use of fuzzy TOPSIS method and evaluation of mixed data (EVAMIX) methods was proposed [10, 3]. The potential for solving NCMP selection problems also has value engineering approach [11].

Table 1. Application of MCDM methods for solving NCMP selection problems: A review.

Reference	MCDM method	Year	Considered NCMP
[5]	combined AHP and TOPSIS	2003	AJM, USM, ECM, CHM, EDM, EBM, LBM
[6]	combined AHP and TOPSIS	2008	USM, WJM, AJM, ECM, CHM, EDM, WEDM, EBM, LBM
[11]	value engineering or value analysis	2008	Different case studies in manufacturing environment
[2]	digraph-based approach	2009	AJM, USM, CHM, EBM, LBM, ECM, EDM, PAM
[7]	ANP	2011	USM, AJM, ECM, CHM, EDM, EBM, LBM, PAM, WEDM, WJM
[8]	DEA	2011	USM, WJM, AJM, ECM, CHM, EDM, WEDM, EBM, LBM, PAM
[9]	PROMETHEE and GAIA	2012	Different case studies from literature [5, 6, 2]
[10]	fuzzy TOPSIS	2013	AJM, WJM, LBM, PAM, Oxy-fuel machining
[3]	EVAMIX	2013	Different case studies from literature [5, 6]

AJM – abrasive-jet machining, USM – ultrasonic machining, ECM – electrochemical machining, CHM – chemical machining, EDM – electro-discharge machining, EBM – electron beam machining, LBM – laser beam machining, WJM – water jet machining, WEDM – wire electrical discharge machining, PAM – plasma-arc machining.

Among these different MCDM methods, high potential for solving ranking and selection problems in manufacturing environment showed a recently developed method i.e. multi-objective optimization on the basis of ratio analysis (MOORA) method. Chakraborty [12] explored the application of the MOORA method to solve different MCDM problems in manufacturing environment including NCMP selection problem. Karande and Chakraborty [13] applied the MOORA method to solve some of the common material selection problems. Dey et al. [14] discussed the application of the MOORA based fuzzy MCDM approach for supply chain strategy selection. Regarding the application of the MOORA method [12, 13, 14] it has been observed that the performance of this method is comparable with other popular and widely used MCDM methods. Moreover, computationally the method is very simple and can be easily implemented.

In this paper, firstly a MCDM model which can be used to select the most suitable NCMP considering different performance criteria has been defined. A pair-wise comparison matrix of the AHP method was then used to determine the relative significance of considered quality criteria, and finally the competitive NCMPs were ranked by using the MOORA method. In order to validate the obtained complete rankings of NCMPs of the MOORA method, the NCMP selection problem was solved also by using the TOPSIS method.

2. NCMPs Selection Problem

Ability to machine advanced materials and fulfill the requirements of high dimensional accuracy and surface finish, made NCMPs one of the most used machining processes in today's industry. Quality performances are very important aspect for NCMPs because it helps to achieve proper tolerance and the required quality of cut, thus eliminating the need for post-processing. These are dependable not only on the machining process itself, but also on the machine tool and its control capabilities, thickness and type of material being cut and also the machining process parameter settings.

Process performances are also important aspect while selecting the most suitable NCMP. It can be considered by taking into account either individually or collectively several indicators such as the specific cutting energy, cutting speed, specific cutting power and the like. Among these, cutting speed is one of the most important factors, and at the same time represents one of the major techno-economic performances of NCMPs.

2.1. Formulation of the NCPM Selection Model

The present MCDM problem is based on the evaluation of four NCMPs i.e. LBM, PAM, EDM and AWJM considering 9 criteria. The NCMPs selection problem was defined considering:

1. *Workpiece material* (WM): This criterion is concerned with the ability of a given NCMP to machine a given workpiece material. It is preferable that a given NCMP has the ability to machine a wider range of materials.

2. *Temperature of the cut* (TC): This criterion incorporates the fact that during different NCMPs there exist temperature effects which may have important impacts on metallurgical properties of the workpiece material.

3. *Economical workpiece thickness* (EWT): Although the considered NCMP can machine a wide spectrum of material thicknesses, for each NCMP there is an interval range of material thickness for which the given NCMP is particularly suitable. In other words, the use of a given NCMP within this range is economical.

4. *Machining accuracy* (MA): The machining accuracy is determined by the characteristics of the coordinate worktable (positioning accuracy) and the quality of the control unit of machine tool.

5. *Kerf taper* (KT): Kerf taper is a special and undesirable geometrical feature inherent to all NCMPs. Kerf taper is normally expressed by kerf taper angle. Reduced kerf taper angle is very important since it allows better positioning of parts, elimination of post-processing and finally saving of material.

6. *Kerf width* (KW): Kerf width and kerf taper are one of the most important quality performance criteria that directly affect final dimensions of the workpiece. It can be defined as the width of material that is removed by a given NCMP. Each NCMP removes a different amount of material i.e. creates different kerf width. The more precise process, the smaller the kerf width is. Generally, it is mainly influenced by the cutting speed.

7. *Quality of surface roughness* (QSR): Assessment of the surface roughness includes the shape and size of irregularities and in practice comes down to analysis of particular sections on the cut surface. Surface roughness parameters defined by international standards are related to the characteristics of the irregularities profiles. Most frequently used parameters for surface roughness are maximum height of the assessed profile (R_z) and the arithmetic mean deviation of the profile (R_a).

8. *Cutting speed* (CS): Higher cutting speeds are always preferable as high cutting speeds save time during machining i.e. enhance productivity.

9. *Burr occurrence* (BO): From the techno-economical point of view, burr occurrence can be regarded as one of the most important criterion for assessing the performance of different NCMPs. Burr free cutting is desired in order to reduce or even eliminate the post-processing of the finished parts. Also, burr formation is undesirable as it causes the release of energy back to the metal leading to increased heat affected zone.

The initial decision matrix for the NCMP selection problem is given in Table 2. The decision matrix was developed based by summarizing the available data from literature [15-18]. It can be observed that except WM and TC, all performance measures of alternatives with respect to criteria are expressed quantitatively.

2.2. Determination of Criteria Weights

Relative importance of considered criteria is derived using the pair-wise comparison matrix of the AHP method. The Saaty nine-point preference scale [20] is adopted for constructing the pair-wise comparison matrix based on the experience of the authors. A criteria compared with itself is always assigned value 1, so the main diagonal of the pair-wise comparison matrix contains values 1 (Table 3).

Table 2. Initial Decision Matrix of NCMPs Selection Problem.

	WM	TC	EWT (mm)	MA (mm)	KT (º)	KW (mm)	QSR R_a (μm)	CS	BO
AWJM	All materials	Cold cut	50	0.05	2	0.8	3.2	Slow	None
LBM	Metals and non-metals excluding highly reflective materials	Hot cut	10	0.015	0.5	0.5	1.6	Fast	Little
PAM	Metals and electrically conductive materials	Very warm cut	10	0.25	8	1.8	12.5	Average	Average
EDM	Electrically conductive materials	Hot cut	100	0.001	0	0.2	0.8	Very slow	None

Table 3. The Pair-wise Comparison Matrix of Considered Criteria.

	WM	TC	EWT	MA	KT	KW	QSR	CS	BO
WM	1	5	3	3	3	3	3	1	1
TC	0.2	1	0.2	0.33	0.2	0.33	0.33	0.2	0.2
EWT	0.33	5	1	3	1	5	3	0.5	0.5
MA	0.33	3	0.33	1	0.33	3	0.33	0.33	0.33
KT	0.33	5	1	3	1	5	3	0.5	0.5
KW	0.33	3	0.2	0.33	0.2	1	0.33	0.2	0.2
QSR	0.33	3	0.33	3	0.33	3	1	0.5	0.5
CS	1	5	2	3	2	5	2	1	0.33
BO	1	5	2	3	2	5	2	3	1

Relative criteria weights (w_j) were determined by calculating the geometric mean ($\mathrm{GM_i}$) of the *i*-th row, and normalizing the geometric means of rows in the comparison matrix by using the following equations:

$$\mathrm{GM_i} = \left(\prod_{j=1}^{n} b_{ij} \right)^{1/n} \tag{1}$$

$$w_j = \mathrm{GM}_i / \sum_{j=1}^{n} \mathrm{GM}_i \tag{2}$$

where b_{ij} denotes the comparative importance of criterion i with respect to criterion j (Table 3).

The criteria weights were obtained as:
$w_j = [0.1966\ 0.0252\ 0.1236\ 0.0544\ 0.1236\ 0.0341\ 0.0763\ 0.1607\ 0.2054]$.

It is observed that the ability of a given NCMP to cut thicker plates of different materials as well as the ability to produce perpendicular high quality cuts without burr occurrence at high cutting speed is assigned the greatest importance.

To ensure the accuracy of obtained criteria weights, a consistency check was performed. For nine considered criteria i.e. for random index of 1.45, consistency index and consistency ratio values of 0.086 and 0.059 were obtained, respectively. These values show that the estimation of criteria weights is reasonable.

3. MOORA Method

The MOORA (Multi-Objective Optimization on the basis of Ratio Analysis) method is one of the newly methods for multi-objective optimization with discrete alternatives proposed by Brauers [19]. The application procedure of the MOORA method is simple and consists of the following steps:

Step 1: The MOORA method starts with setting the goals and identification of the relevant criteria for evaluating available alternatives.

Step 2: In this step, based on the available information about the alternatives, decision-making matrix or decision table is set. Each row refers to one alternative, and each column to one criterion. The initial decision matrix, X, is:

$$X = \left[x_{ij} \right] = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{3}$$

where x_{ij} is the performance measure of i-th alternative with respect to j-th criterion, m is the number of alternatives and n is the number of criteria.

For ranking or selecting one or more alternatives from a set of available ones, the MOORA method considers both beneficial and non-beneficial criteria and in this step categorization of considered criteria is made. Also, in this step, weights are assigned to criteria, w_j (j=1,2,...,n). These weights can be determined using the entropy method or AHP method.

Step 3: Here a ratio system is developed in which each performance measure of an alternative on a criterion is compared to a denominator which is a representative for all the alternatives concerning that criterion. For this denominator the square root of the sum of squares of each alternative per criterion is chosen [19]. This ratio can be expressed as:

$$x_{ij}^{*} = x_{ij} / \sqrt{\sum_{i=1}^{m} x_{ij}^{2}}, \quad \left(j = 1, 2, ..., n \right) \tag{4}$$

where x_{ij}^{*} is a dimensionless number from the interval [0,1] and represents the normalized performance measure of i-th alternative with respect to j-th criterion.

Step 4: In this step x_{ij}^{*} values are added in case of beneficial criteria and subtracted in case of non-beneficial criteria. Then the optimization problem becomes:

$$y_i = \sum_{j=1}^{g} w_j \cdot x_{ij}^* - \sum_{j=g+1}^{n} w_j \cdot x_{ij}^* \tag{5}$$

where g is the number of criteria to be maximized (beneficial criteria), n is the number of criteria to be minimized (non-beneficial criteria) and y_i is the assessment value (composite score) of the i-th alternative with respect to all considered criteria.

Step 5: Assessment values, y_i, may be positive or negative depending upon the total number of beneficial and non-beneficial criteria in the decision matrix. The ranking of the alternatives is determined on the basis of the descending order of the assessment values. Thus, the best alternative has the highest y_i value and the worst alternative has the lowest y_i value.

The following flow chart (Fig. 1) illustrates the application steps of the MOORA method for solving decision making problems.

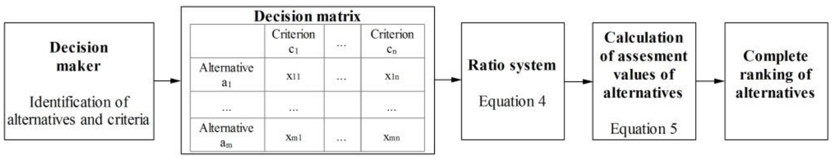

Fig. 1. Application procedure of the MOORA method.

4. Results and Discussion

In this section applicability of the MOORA method for selection of the most appropriate NCMP considering different criteria was discussed.

The detailed computational procedure of the MOORA method for solving the NCMP selection problem considering different criteria is as follows. Among the considered criteria, WM, EWT and TS are beneficial criteria where higher values are desirable. On the other hand, TC, MA, KT, KW, QSR and BO are non-beneficial criteria where smaller values are preferable. Firstly, the qualitative information of four criteria, i.e., WM, TC, TS and BO are converted into appropriate quantitative data (crisp values) using the 10-point scale [21]. Hence the decision matrix has the following form (Table 4).

Table 4. Decision Matrix of the NCMP Selection Problem.

	WM	TC	EWT (mm)	MA (mm)	KT (degree)	KW (mm)	QSR (µm)	CS	BO
AWJM	9	0.115	50	0.05	2	0.8	3.2	3	0
LBM	7	0.495	10	0.015	0.5	0.5	1.6	7	3
PAM	5	0.895	10	0.25	8	1.8	12.5	5	5
EDM	3	0.495	100	0.001	0	0.2	0.8	1	0

Table 5 shows the normalized performance measures of alternatives with respect to the considered criteria, as obtained by using Eq. 4. Subsequently by using Eq. 5, the assessment values (composite scores) of all alternatives with respect to the considered criteria are estimated. Table 6 exhibits these results of the MOORA method upon which complete ranking of the NCMPs was obtained.

Table 5. Normalized Decision Matrix of the NCMP Selection Problem.

	WM	TC	EWT (mm)	MA (mm)	KT (degree)	KW (mm)	QSR (μm)	CS	BO
AWJM	0.7028	0.1007	0.4437	0.1958	0.2421	0.3918	0.2457	0.3273	0
LBM	0.5466	0.4334	0.0887	0.0587	0.0605	0.2449	0.1228	0.7638	0.5145
PAM	0.3904	0.7837	0.0887	0.9789	0.9684	0.8815	0.9596	0.5455	0.8575
EDM	0.2343	0.4334	0.8874	0.0039	0	0.0979	0.0614	0.1091	0

Table 6. Assessment Values and Ranking of Considered NCMPs.

	y_i	Rank
AWJM	0.1704	1
LBM	0.0962	3
PAM	-0.2967	4
EDM	0.1541	2

It is observed that AWJM is the most suitable NCMP considering material application and different performance criteria. From Table 6, it is revealed that EDM is the second best choice, and that LBM is third choice. PAM is obtained as the least preferred NCMP. Negative assessment value of PAM is due to fact that the considered MCDM problem has six non-beneficial criteria against three beneficial criteria.

For the purpose of validation, the same NCMPs selection problem is solved by using the TOPSIS method as one of the most commonly used MCDM methods. The computational details and step-by-step procedure of the TOPSIS method is explained in details in [22]. The positive ideal solution (S_+), negative ideal solution (S_-) and relative closeness to the ideal solution (P_i) for each alternative are given in Table 7.

Table 7. Assessment Values and Ranking of Considered NCMPs.

	S_+	S_-	P_i
AWJM	0.0961	0.2368	0.7114
LBM	0.1484	0.1988	0.5726
PAM	0.2619	0.0766	0.2263
EDM	0.1401	0.2517	0.6424

As a result of the application of the TOPSIS method (Table 7) the complete ranking in descending order was obtained as AWJM-EDM-LBM-PAM. This result suggests that there is a perfect correlation between rankings obtained by MOORA and TOPSIS methods.

The MOORA method can simultaneously take into account any number of criteria and offer a very simple computational procedure. As this method is based on simple ratio system, it involves the least amount of mathematical computations. This has the double benefit for decision makers. On the one hand, the implementation of the MOORA method does not necessarily requires strong background in mathematics and operational research. On the other hand, unlike many other MCDM methods, which require software packages in order to efficiently solve a given MCDM problem, all mathematical calculations of the MOORA can be easily worked in MS Excel.

Regarding required application steps for solving decision making problems, the MOORA method has advantage over other MCDM methods. While only five steps are needed to solve a particular decision making method using the MOORA method, TOPSIS method requires nine steps [22]. Also, unlike many other MCDM methods, the normalization of decision matrix is done by vector normalization procedure using only one normalization equation regardless of the nature of criterion (beneficial or non-beneficial). In such way there is no need to use additional normalization equations or to transform non-beneficial to beneficial criteria and vice versa. As noted by Chakraborty [12], another major advantage of this method is that its calculation procedure is not affected by the introduction of any additional parameters as it happens in case of other MCDM methods.

The particular benefit of the MOORA method is reflected in the fact that it can be used in situations where decision maker is faced with the problem of determining criteria weights. In such cases for the purpose of optimization, Eq. 5 becomes:

$$y_i = \sum_{j=1}^{g} x_{ij}^{*} - \sum_{j=g+1}^{n} x_{ij}^{*} \qquad (6)$$

5. Conclusions

In this paper, a MCDM model for the selection of the most appropriate NCMP considering different criteria, particularly related to quality performance, has been defined and solved by using the MOORA method. The obtained results suggested that AWJM is the best alternative, while EDM is the second one. LBM and PAM were the third and fourth alternatives in the rank. In order to validate the obtained rankings of NCMPs obtained by the application of the MOORA method, the considered NCMPs selection problem was solved by using the TOPSIS method. It was observed that ranking of competitive NCMPs exactly match. The main advantage of the MOORA method is that it can take into account any number of criteria, both quantitative and qualitative, and offer a very simple computational procedure. Moreover, the implementation of MOORA method does not necessarily requires strong background in mathematics and operational research as well the use of specialized software packages since it can be easily implemented in MS Excel.

The advantages and benefits of the MOORA method over other available MCDM methods are reflected in the following facts: (*i*) the application of the MOORA method for solving a particular decision making problems requires fewer application steps, (*ii*) single equation is required for the purpose of decision matrix normalization irrespective of the nature of criterion, (*iii*) it can be applied in situations where criteria weights are not explicitly given.

Further researches will focus on the consideration of additional criteria that influence the NCMP selection problem and comparative analysis of the MOORA method for solving other selection problems in manufacturing environment.

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