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SELECTION OF NON-CONVENTIONAL MACHINING PROCESSES USING MCDM SOLVER

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Abstract. *The importance and application of non-conventional machining processes (NCMPs) in the modern production environment is increasing. In order to select the most appropriate of the available NCMPs, a number of different requirements, capabilities, limitations and advantages of each should be considered. As the NCMP selection problem involves the consideration of different conflicting criteria with different relative importance, the multi-criteria decision making (MCDM) methods are very useful in the systematical selection of the most appropriate NCMP. This paper presents the application of a decision support system (MCDM Solver) to solve an NCMP selection problem which has been defined considering different performance criteria of four most widely used NCMPs. The results obtained using the MCDM Solver proposed abrasive water jet machining (AWJM) as the best ranked choice.*

Key words: *Non-conventional machining processes, Multi-criteria decision making, Selection, Decision support system, MCDM Solver*

1. INTRODUCTION

Technical and technological progress and rapid development in many different areas (aeronautical, rocket, space, nuclear, electronic, computer, biomedical, etc.) has led to a continuous development of both the production and application of a wide range of new and advanced materials. These are materials with significantly better mechanical and tribological properties, high tensile strength and hardness, high resistance to temperatures, wear and corrosion, etc. The processing of advanced materials by classical conventional production technologies and methods is much more difficult and costly and is in some cases even impossible. Therefore, in parallel, new advanced processing technologies and methods, such as non-conventional machining processes (NCMPs), are being developed and further improved, offering higher productivity rates along with the economy of material processing.

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In conventional machining, there must be a direct contact between the tool and the work material, while NCMPs use a direct form of energy (mechanical, thermal or chemical) for material removal. It employs modern processing technologies including water jet, laser beam, electric arc, electric discharge, plasma arc and electron beam machining, etc. In these machining processes, there is no direct contact between the tool and the workpiece. NCMPs are generally used when traditional methods are not technically or economically feasible such as machining of complex shapes, high accuracy and surface finish requirements, low cutting forces or clamping forces requirements and so on.

Several NCMPs are being increasingly used for processing of different engineering materials in the modern production environment. Thanks to the high degree of accuracy, higher tool life, high removal rate, great surface finish as well as the ability to easily machine complex shapes of advanced materials, NCMPs are very important and even inevitable in modern production. Laser beam machining (LBM), abrasive water jet machining (AWJM), electrical discharge machining (EDM) and plasma arc machining (PAM) are particularly used in the industry for materials processing. Each of these NCMP is a very complex machining process having its own unique characteristics, prerequisites, advantages and limitations.

There is often a need to make strategic decisions for the selection of technologies and machines in production companies, and this requires the possession of certain competencies and professional knowledge. Correct decision-making ensures the long-term survival of the company and the achievement of high market competitiveness through increased productivity, product quality, flexibility and cost competitiveness. Since the price of NCMP machine tools is very high, inadequate selection has long-term consequences on the business and the success of the entire company. Hence, the selection of the most appropriate NCMP for a particular production company is of utmost importance. It is also a challenging and time-consuming task for decision makers (managers, stakeholders, business owners), where a large number of data and parameters must be processed [1].

The selection of the most appropriate NCMP was considered in this paper as a multi-criteria decision making (MCDM) problem with nine different performance criteria. This problem can be successfully solved using some of the MCDM methods which have the capabilities to generate decision rules while considering relative significance of considered criteria upon which the complete ranking of alternatives is determined [2].

A decision support system (DSS) is a special class of information systems oriented toward the decision-making process and aimed at supporting mainly business decision-doing processes. DSS is a symbiosis of information systems, application of functional knowledge and ongoing decision-making processes [3]. Its main goal, as well as the goals of other information systems, is to improve the efficiency and effectiveness of an organization.

This paper is aimed at applying a developed DSS named the MCDM Solver for selecting the most appropriate NCMP. The MCDM Solver was used to determine the relative significance of considered NCMPs performance criteria and perform the ranking of the competitive NCMPs.

2. NCMPs Selection Problem

The continuous development of new and the improvement of the existing NCMPs have caused the appearance of many different processes and technologies. The ability to machine advanced materials and fulfill the requirements of high dimensional accuracy and surface finish has made NCMPs one of the most used machining processes in today's industry. Quality performance is a very important aspect for NCMPs because it helps to achieve proper tolerance and the required quality of the cut, thus eliminating the need for post-processing. These performances 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 the machining process parameter settings [4].

Process performance is also an important aspect in the selection of 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 Problem

In this study four NCMPs (AWJM, LBM, PAM and EDM) were evaluated based on nine criteria. Nine performance criteria of the NCMPs selection problem [4] were considered:

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 are temperature effects which may have an important impact on mechanical and technological 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 appropriate. In other terms, using a given NCMP within this range is economical.
4. **Machining accuracy (MA)**: Machining accuracy is determined by the characteristics of the coordinate worktable (positioning accuracy) and the quality of the machine tool control unit.
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. Reducing 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 among the most important quality performance criteria which 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 creating different kerf width. For a more precise process, smaller kerf width is preferable. 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 analyzing the particular sections on the cut surface. Surface roughness parameters defined by

international standards are related to the characteristics of the irregularity's profiles. Most frequently used parameters for surface roughness are the 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 could be regarded as one of the most important criteria 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. Burr formation is undesirable as it causes the release of energy to the base metal leading to increased heat affected zone.

The initial decision matrix for the NCMP selection problem is given in Table 1. The decision matrix was developed based on summarizing the available data obtained from the literature [5-9]. It can be observed that except WM, TC, CS and BO, all attribute values in the decision matrix are expressed quantitatively.

Table 1 Initial Decision Matrix of NCMPs Selection Problem [4]

NCMPs	WM	TC	EWT (mm)	MA (mm)	KT (°)	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

3. MCDM SOLVER

The MCDM Solver is an "on-line" DSS which was developed within the doctoral dissertation of Dušan Petković [10]. The developed DSS is located on the "Virtuode" Company web site (https://virtuodeportalapp.azurewebsites.net/) and it is available to anyone who registers by creating an account (Fig. 1). This DSS offers the possibility of working with maximization, minimization as well using the target criteria [10].

Necessary input data for the application of the MCDM Solver are:

• Initial matrix of the decision-making problem with the target value of criteria (Step 1);

- η - Confidence level of the decision maker in significance to the selected criteria (where η=1 corresponds to confidence level of 100%, while η=0 corresponds to confidence level of 0%);
- Pairwise significance evaluation of the selected criteria.

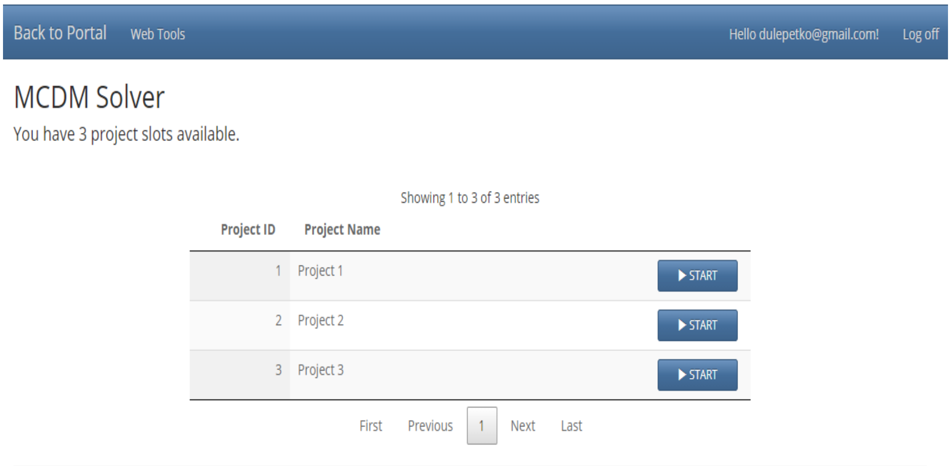


Fig. 1 MCDM Solver – initial layout

Based on the input data, the MCDM Solver is able to determine the values of the criteria weights (Step 2) and perform the ranking of alternatives (Step 3) with the corresponding values by means of the following MCDM methods: Extended TOPSIS [11], Comprehensive VIKOR [12] and Comprehensive WASPAS [10, 13].

The developed DSS architecture is flexible and can be easily upgraded, so the inclusion and analysis of new models that will come in the future is enabled. The MCDM Solver has a user-friendly interface, which enables a simple and efficient way of entering the necessary input data [14]. Its application significantly simplifies the solution process of MCDM problems, especially material selection and selection problems in machining. It does not require expert knowledge of the decision-making theory by the user (decision maker) and is able to easily handle large decision-making matrices [14, 15].

4. DATA PREPARATION FOR THE MCDM SOLVER

In this section the applicability of the MCDM Solver for the selection of the most appropriate NCMP considering different criteria is discussed. The detailed procedure of using the MCDM Solver method for solving the considered NCMPs selection problem considering different criteria is described. Among the considered criteria, WM, EWT and CS are the maximization criteria where higher values of attributes are preferable, while TC, MA, KT, KW, QSR and BO are the minimization criteria where smaller values of attributes are preferable. Also, in order to make the procedure applicable for the MCDM Solver (methods), all qualitative data - defined by using linguistic terms (WM, TC, CS and BO criteria performances) - was converted into quantitative data.

For this purpose, an 11-point scale is used for better understanding and representation of the qualitative attributes and converting linguistic terms into corresponding dimensionless numbers [10], as shown in Table 2. Additionally, the performance of the KT criterion for the EDM process is equal to 0, but in this case the value was set to 0.01 (near zero). The reason was the MCDM Solver's inability to operate with zero values due to the WASPAS method which is incorporated in the DSS. Hence, the initial decision matrix was converted into the matrix which can be used by the MCDM Solver, as shown in Table 3.

Table 2 Qualitative criteria and conversion values in the 11-point scale format

Qualitative measure of material selection factor assigned	Value
Exceptionally low	0.045
Extremely low	0.135
Very low	0.255
Low	0.335
Below average	0.410
Average	0.500
Above average	0.590
High	0.665
Very high	0.745
Extremely high	0.865
Exceptionally high	0.955

Target values for all nine criteria are given in the last row of Table 3. Based on the input data, i.e., Table 3, confidence level of η=1 and pairwise evaluation of criteria significances, criteria weights were determined.

Table 3 Decision Matrix of NCMPs Selection Problem

NCMPs	WM	TC	EWT (mm)	MA (mm)	KT (°)	KW (mm)	QSR R_a (μm)	CS	BO
AWJM	0.955	0.045	50	0.05	2	0.8	3.2	0.335	0.045
LBM	0.665	0.5	10	0.015	0.5	0.5	1.6	0.665	0.335
PAM	0.5	0.955	10	0.25	8	1.8	12.5	0.5	0.5
EDM	0.335	0.5	100	0.001	0.01	0.2	0.8	0.255	0.045
Target value	***0.955***	***0.045***	***100***	***0.001***	***0.01***	***0.2***	***0.8***	***0.665***	***0.045***

Using the MCDM Solver one can simultaneously consider any number of criteria and perform different computational procedures (depending on the selected methods) in a very simple and time-saving way. As this approach is based on the simple activity of data preparation and pair-wise comparison of the criteria, the user activity is mostly oriented toward generating as precise decision matrix as possible. This has a double benefit for decision makers. Firstly, using the MCDM Solver does not necessarily require a strong background in mathematics, decision-making theory and operational research. On the other hand, unlike many other MCDM methods, whose application requires specialized software packages in order to efficiently solve a given MCDM problem, all mathematical calculations and ranking are performed by this DSS, which can be run in the online as well as the offline mode.

5. RESULTS AND DISCUSSION

Based on the input data, i.e., decision matrix, confidence level of η=1 and pairwise evaluation criteria significances, criteria weights are determined (as shown in Fig. 2).

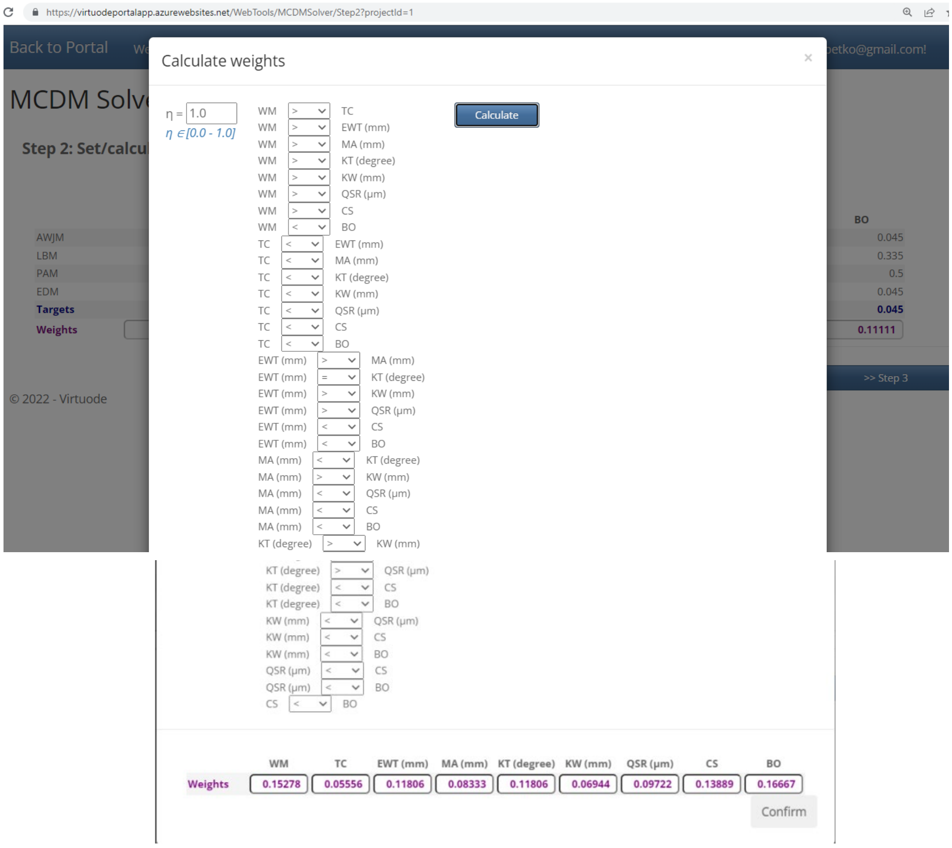
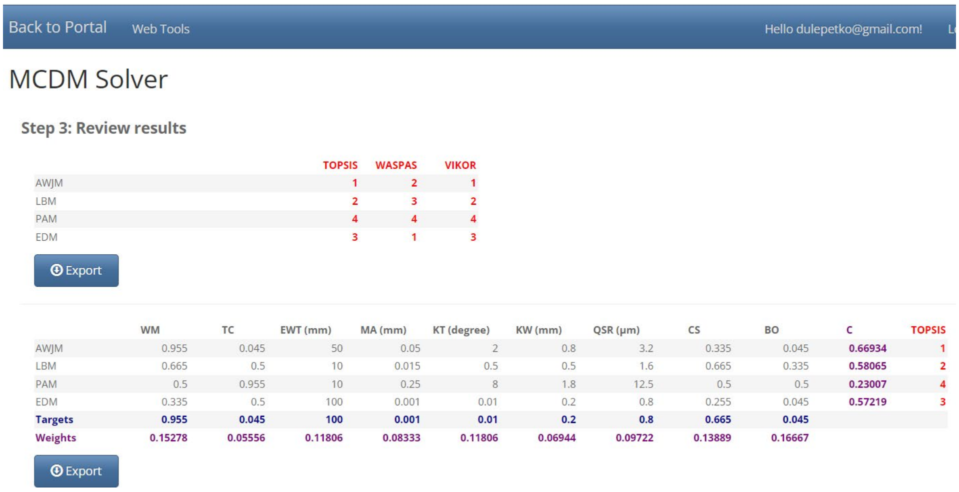


Fig. 2 Pairwise significance evaluation of the criteria

The MCDM Solver calculation of the subjective weights (confidence level of η=1) of criteria was carried out based on the modified digital logic (MDL) method [16]. This is a pair-wise comparison method, where participants/criteria are presented with a worksheet and asked to compare the importance of two criteria at a time as given in Fig 2. Thereby, BO, WM and CS are considered as the most significant criteria with weights of 0.167, 0.153 and 0.139, respectively. Criteria such as EWT and KT are equally significant with weights of 0.118. The QSR, MA, KW and TC are the least significant criteria with weights of 0.097, 0.083, 0.069 and 0.056, respectively.

Step 3 involves ranking the NCMPs by means of the MCDM Solver. Ranking orders of NCMPs using different MCDM methods (TOPSIS, WASPAS and VIKOR) are shown in Fig. 3. In order to make ranking results clearer and more readable, these are also shown in Table 4. The aggregated rank of NCMPs is also shown in this table due to the differences in the obtained results which are the consequence of different MCDM methods.

As can be seen, the best ranked NCMP is AWJM, while PAM is the worst ranked NCMP. The ranking results also show that there is total agreement between the TOPSIS and VIKOR results for all NCMPs. On the other hand, WASPAS and the other methods are totally matched only for the worst ranked NCMP - PAM. The best ranked NCMP by the WASPAS method is EDM (third ranked by the others) while the second ranked NCMP is AWJM (best ranked by the other MCDM methods).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MCDM Solver

Step 3: Review results

	TOPSIS	WASPAS	VIKOR
AWJM	1	2	1
LBM	2	3	2
PAM	4	4	4
EDM	3	1	3

Export

	WM	TC	EWT (mm)	MA (mm)	KT (degree)	KW (mm)	QSR (μm)	CS	BO	C	TOPSIS
AWJM	0.955	0.045	50	0.05	2	0.8	3.2	0.335	0.045	0.66934	1
LBM	0.665	0.5	10	0.015	0.5	0.5	1.6	0.665	0.335	0.58065	2
PAM	0.5	0.955	10	0.25	8	1.8	12.5	0.5	0.5	0.23007	4
EDM	0.335	0.5	100	0.001	0.01	0.2	0.8	0.255	0.045	0.57219	3
Targets	0.955	0.045	100	0.001	0.01	0.2	0.8	0.665	0.045		
Weights	0.15278	0.05556	0.11806	0.08333	0.11806	0.06944	0.09722	0.13889	0.16667		

Export

Fig. 3 Ranking results of NCMPs

Table 4 shows the results of the three MCDM methods, i.e., TOPSIS, WASPAS and VIKOR, upon which the complete ranking of the NCMPs was obtained. In such cases when the ranking results do not match totally, it is necessary to propose an aggregate solution, based on the results obtained from several methods. In this case, it is not very complicated, because the two methods completely match, while the results of the third method do not differ too much, at least not in terms of the worst solution. The validation of the methodology is done by using the MCDM Solver with the three MCDM methods.

It is observed that AWJM is the most suitable NCMP considering material application and different performance criteria. From Table 4, it is revealed that LBM is the second-best choice, but EDM is the third, relatively close to LBM. PAM is obtained as the least preferred NCMP.

Table 4 Ranking results obtained by using the MCDM Solver

NCMPs	TOPSIS	C_i	WASPAS	Q_i	VIKOR	P_i	Agregate rank
AWJM	1	0.669	2	0.402	1	0.003	1
LBM	2	0.581	3	0.284	2	0.107	2
PAM	4	0.230	4	0.149	4	1.000	4
EDM	3	0.572	1	0.709	3	0.346	3

6. CONCLUSION

In this paper, an MCDM model for the selection of the most appropriate NCMP considering different criteria, particularly related to quality performance, was defined and solved by using the MCDM Solver. The application of the developed DSS, named the MCDM Solver, for solving an NCMPs selection problem is considered. Thanks to the MCDM Solver, the NCMPs selection process is carried out much faster and more easily, because it comes down to the selection of potential NCMPs, consideration of the most important evaluation criteria and pair-wise significance evaluation of the selected criteria. Hence, a complex mathematical apparatus was avoided and the decision-making rule generation and its application to the ranking process was performed faster, more comfortably and reliably.

The obtained results proposed that AWJM is the best alternative, while LBM is the second one. EDM is the third preferable choice but very close to LBM - the second ranked NCMP. It turned out that PAM was undoubtedly the least preferred NCMP within the considered circumstances.

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