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APPLICATION AND COMPARISON OF MCDM METHODS FOR THE ASSESSMENT OF FIBER LASER CUTTING

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Abstract. *Fiber laser cutting, as one of the more recent and complex production processes, is characterized by a large amount of input parameters and output performances. Desired output performances in the fiber laser cutting process are often of conflicting natures. In order to determine the best trade-off between desired output performances, i.e., criteria, several multi criteria decision making (MCDM) methods were employed to evaluate and rank different fiber laser cutting conditions. The methods used were Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Weighted Aggregated Sum Product Assessment (WASPAS) and Evaluation based on Distance from Average Solution (EDAS). Box-Behnken experimental design was employed for 3 selected input parameters (focus position, cutting speed and assist gas pressure). All three parameters were systematically varied on three levels in accordance with the selected Box-Behnken experimental design in order to define 15 possible alternative cutting regimes for which values of all selected criteria were measured. The measured criteria, based on which alternatives were finally ranked, were cut quality, material removal rate, kerf width, cutting efficiency and assist gas price. All employed methods were consistent in ranking the alternatives, and alternative 4 was ranked as the best possible alternative, while alternative 1 was the worst possible alternative.*

Key words: *Fiber laser cutting, MCDM, TOPSIS, WASPAS, EDAS, AHP*

1. INTRODUCTION

Laser cutting is a technology that uses a laser beam to heat, melt and/or vaporize the workpiece material to produce a cut. To ensure dross free cutting, the flow of auxiliary assist gas, typically oxygen or nitrogen, is used coaxially to the laser beam. Laser cutting can produce a high-quality cut surface. In order to achieve desired cut quality characteristics, numerous input parameters must be tuned properly. Generally, numerous cut quality characteristics are determined by choice of laser cutting system, beam quality, available power, material and assist gas properties, etc. [1]. Fiber laser cutting has emerged as a prominent technology among new technologies, owing to its unmatched precision,

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high cutting speeds, and versatility. These features have positioned it as a primary technology for cutting, engraving, and marking various materials, ranging from wood to metal [2], [3]. Several process parameters, including cutting speed, laser power, focus position, nozzle standoff distance, assist gas pressure, and nozzle diameter significantly affect the quality characteristics of laser cutting. Despite the collective influence of these input parameters on laser cutting quality, their individual impacts are frequently not thoroughly examined or understood. Moreover, these input parameters often exert diverse and sometimes opposing effects on the quality characteristics of laser cuts, i.e., laser cutting conditions that are the most suitable for minimization of surface roughness may not be even optimal for minimization of kerf width [4]. The problem of determining the best possible combination of input parameters for achieving the desired output performances can be classified as the problem of multi criteria decision making (MCDM). MCDM problems can be solved by many MCDM methods. These methods are systematic approaches that employ mathematical models, decision matrices, and decision rules to aid in the decision-making process and find the most suitable solution considering the diverse criteria involved. MCDM problems in machining can be solved by different MCDM methods [5], out of which the most used are AHP [6], [7], TOPSIS [8], [9], WASPAS [4], [10], EDAS [11], etc.

MCDM methods can be used to solve problems in both traditional and non-traditional machining processes. Khan and Maity used the TOPSIS method for the selection of the optimal process parameter in turning of pure titanium [12]. Divya et al. [13] reviewed applications of MCDM methods: TOPSIS, VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR in Serbian), Multi-Objective Optimization on the basis of Ratio Analysis (MOORA), and AHP for process parameter optimization in the turning process. Kumar and Singh used an integrated MCDM approach for the optimization of CNC green milling process parameters with the TOPSIS-CRITIC and MOORA-CRITIC methods [14]. Kalita et al. [15] used the weighted sum model (WSM), weighted product model (WPM), weighted aggregated sum product assessment (WASPAS), MOORA, evaluation based on distance from average solution (EDAS) and TOPSIS MCDM methods for parametric optimization of the milling process. Singaravel et al. [16] used TOPSIS for the optimization of friction stir welding process parameters. Yuvaraj and Pradeep Kumar [17] used TOPSIS for the multi-response parameter optimization of the abrasive water jet (AWJ) cutting process. Muthuramalingam et al. [18] used the Taguchi – Data Envelopment Analysis based Ranking (DEAR) method for the optimization of process parameters in AWJ machining. Madić et al. [3] applied the WASPAS method for the assessment of different laser cutting conditions in CO2 laser cutting of stainless steel considering cut quality characteristics. Madić et al. [9] compared the WASPAS and OCRA methods for the assessment of laser cutting conditions in CO_2 laser cutting of aluminum alloy with respect to six criteria, three related to quality (perpendicularity of the cut, kerf width, and surface roughness) and three related to process, cost and productivity performances. Das and Chakraborty [19] applied the grey correlation-based EDAS method for simultaneous parametric optimization of a photochemical machining process, laser assisted jet electrochemical machining process and abrasive water jet drilling process. Trung [20] applied five MCDM methods, i.e., EDAS, MARCOS, MOORA, TOPSIS and PIV, to determine the best values of cutting parameters in the milling process. In order to achieve low surface roughness and a large value of material removal rate (MRR), Phipon et al. [21] used and compared the EDAS, WASPAS, MOORA and TOPSIS methods in determining optimal process parameters for laser beam micro engraving on silicon carbide. Tiwary and Shivakoti [22] attained an optimal process parameters combination using the EDAS method for laser beam micro marking on Inconel 625 super-alloy.

The goal of the present study is to develop a MCDM model for fiber laser cutting of S235 steel in order to evaluate and rank different alternative laser cutting conditions. The laser cutting experiment, planned according to the Box-Behnken experimental design with 15 trials of which 3 were in the central point, provided a set of experimental data upon which the MCDM model was developed. Multi-criteria analysis of fiber laser cutting process performances was conducted by using the TOPSIS, WASPAS and EDAS methods while considering cut quality, material removal rate, kerf width, cutting efficiency and assist gas price as assessment criteria. The relative significance of criteria was determined by the application of the geometric mean method of the analytic hierarchy process (AHP).

2. EXPERIMENTAL PROCEDURE

The workpiece material used in this experimental study was 3mm thick non-alloyed structural steel S235 [23]. While conducting the experimental study, the following conditions were constant: maximum laser power of 2 kW, standoff distance of 1mm, assist gas type (Oxygen), nozzle diameter of 1.2 mm and laser head. For the assessment of the effect of parameters on cut quality characteristics, three laser cutting parameters: focus position (f), cutting speed (v) and assist gas pressure (p) were varied, each on three levels in accordance with the Box-Behnken experimental design. The parameter levels used in this experiment are given in Table 1.

Table 1. Parameters and parameter levels

Level	f(mm)	v(m/min)	p(bar)
-1	1	1.8	0.75
0	1.5	2.7	0.85
+1	2	3.6	0.95

In the experiment 15 experimental trials were conducted with 3 experimental trials in the central point. To eliminate any kind of subjectivity and minimize effects of unknown or uncontrolled variables, experimental trials were conducted in a randomized order, while effects of all external factors were held constant. Experimental trials were conducted in the manufacturing environment with a Gweike fiber laser LF3015CNR 2000W [24]. The value of kerf width was measured with a combined measuring system DeMeet 443-Combo [25].

3. MCDM MODEL

In the creation of the MCDM model, individual experimental trials developed in accordance with the Box-Behnken experimental design were used as alternatives. Cut quality (Cq (scale 1-9)), material removal rate (MRR (mm^3/min)), kerf width (Kw (mm)) cutting efficiency (Ce(mm^3/J)) and assist gas price (AGP (EUR/h)) were used as assessment criteria. Based on kerf width values, MRR was calculated as the product of kerf width, cutting speed and sheet thickness, for each experimental trial. Likewise, AGP values were obtained considering the consumption of the assist gas, based on assist gas pressure, nozzle diameter, and the price for oxygen (3.5 EUR/m^3). Assessment criteria Cq, MRR and Ce should be maximized while Kw and AGP should be minimized. The full MCDM model with attribute values for all 15 alternatives is given in Table 2.

Table 2. MCDM model

Trial	f	v	p	Cq	MRR	Kw	Ce	AGP
1	1	1.8	0.85	5	2079.0	0.385	0.045	5.17
2	2	1.8	0.85	6	2732.4	0.506	0.045	5.17
3	1	3.6	0.85	3	3564.0	0.33	0.09	5.17
4	2	3.6	0.85	8	5022.0	0.465	0.09	5.17
5	1	2.7	0.75	9	3110.4	0.384	0.0675	4.9
6	2	2.7	0.75	9	3879.9	0.479	0.0675	4.9
7	1	2.7	0.95	8	3110.4	0.384	0.0675	5.45
8	2	2.7	0.95	9	3985.2	0.492	0.0675	5.45
9	1.5	1.8	0.75	6	2397.6	0.444	0.045	4.9
10	1.5	3.6	0.75	6	4525.2	0.419	0.09	4.9
11	1.5	1.8	0.95	7	2430.0	0.45	0.045	5.45
12	1.5	3.6	0.95	7	4557.6	0.422	0.09	5.45
13	1.5	2.7	0.85	9	3515.4	0.434	0.0675	5.17
14	1.5	2.7	0.85	9	3499.2	0.432	0.0675	5.17
15	1.5	2.7	0.85	9	3596.4	0.444	0.0675	5.17

Not all of the assessment criteria are of equal importance in this MCDM problem. In the context of the MCDM framework, the relative importance of criteria is represented by assigning them a criteria weight. The relative importance of assessment criteria is determined by using the geometric mean method of the analytic hierarchy process (AHP) method [26]. The Saaty nine-point preference scale is adopted for constructing the pair-wise comparison matrix based on the experience of the authors. A criterion compared with itself is always assigned value 1, so the main diagonal of the pairwise comparison matrix contains values 1 (Table 3). The values of criteria weights Wi are given in the last column of Table 3.

Table 3. Pairwise comparison matrix

Criteria	C1	C2	C3	C4	C5	W_i
C1	1.000	2.000	3.000	4.000	5.000	0.416
C2	0.500	1.000	2.000	3.000	4.000	0.262
C3	0.333	0.500	1.000	2.000	3.000	0.161
C4	0.250	0.333	0.500	1.000	2.000	0.099
C5	0.200	0.250	0.333	0.500	1.000	0.062

3.1 TOPSIS method

TOPSIS, devised by Hwang and Yoon [27], is a multi-criteria decision-making tool that has undergone evaluation by decision makers at various levels. It employs a compensatory aggregation approach to pinpoint the optimal choice from a given set of alternatives. The methodology operates on the principle that the best alternative should be as close as possible to the positive-ideal solution (S_i^*) while being as far as possible from the negative-ideal solution (S_i^-). Initially, the alternatives are assessed based on their resemblance to an ideal solution, which represents an ideal outcome in all aspects, although it may not be practically attainable. Alternatives demonstrating greater similarity to the best solution are assigned higher ratings than those with lower similarity values. In addition to its original form, TOPSIS can also be used in modified forms, i.e., modified TOPSIS [28], behavioral TOPSIS [29] or fuzzy TOPSIS [30].

3.2 WASPAS method

WASPAS, devised by E. K. Zavadskas [31], is a MCDM method that was created by combining two very well-known MCDM methods, i.e., Weighted Sum Model (WSM) and Weighted Product Model (WPM). The integration of the WSM and WPM methods within the WASPAS framework seeks to mitigate certain constraints inherent in individual models, thereby furnishing a more all-encompassing decision-making structure. The procedural sequence and mathematical expressions employed in WASPAS are subject to variability, permitting adaptability to the distinctive attributes of the pertinent decision problem. The relative importance of alternatives is determined for both WSM ($Q_i^{(1)}$) and WPM ($Q_i^{(2)}$). Finally, the relative importance for the WASPAS method is calculated as a sum of relative importances multiplied with λ and (1- λ) respectively. Alternatives are then ranked based on the value of relative importance: alternatives with higher value are considered as more desirable alternatives, while alternatives with low values of relative importance are considered as non-desirable alternatives. In addition to its original form, WASPAS can also be used in modified forms, i.e., spherical fuzzy WASPAS (SF-WASPAS) [32], interval-valued intuitionistic fuzzy numbers WASPAS (WASPAS-IVIF) [33], ordered fuzzy WASPAS (OFN-WASPAS) [34] or interval type-2 fuzzy sets extended WASPAS [35].

3.3 EDAS method

EDAS, devised by Keshavarz Ghorabaee et al. [36], is introduced for multi-criteria inventory classification (MCIC) problems, but it can be successfully used for MCDM problems. MCDM methods like TOPSIS and VIKOR use positive ideal and negative ideal solution and distances from them for ranking the alternatives. EDAS, on the other hand, uses positive and negative distances from average solution for evaluation of the alternatives. The average solution is determined using a simple arithmetic mean of performance values of alternatives. Two values are calculated, i.e., positive distance from average solution (PDA) and negative distance from average solution (NDA), and they are used for the ranking of the alternatives. Alternatives with higher values of PDA and lower values of NDA are desirable, while alternatives with low values of PDA and high values of NDA are non-desirable. PDA and NDA are used in their summed and weighted form as NSPi and NSNi, while the appraisal score is calculated as a halved sum of NSPi and NSNi and denoted by Asi. In addition to its original form, EDAS can also be used in modified forms, i.e., Stochastic EDAS [37], enhancement EDAS methods based on prospect theory [38], fuzzy EDAS [39], integrated regret-theory EDAS [40] or grey correlation-based EDAS [41].

4. RESULTS AND DISCUSSION

The results of the application of the TOPSIS method for the proposed MCDM model are represented in Table 4 and Fig. 1. From the results it can be clearly seen that the alternative with the best overall performance Vi is alternative 4, while the second and third best ranked alternatives by overall performance are alternatives 8 and 6, respectively. The worst ranking alternative by overall performance is alternative 1, while the second and third worst alternatives are alternatives 3 and 9.

Table 4. Ranking of the alternatives - TOPSIS method

Alternative	S_i^*	S_i^-	V_i	Rating
1	0.082	0.031	0.274	15
2	0.065	0.044	0.405	12
3	0.090	0.037	0.290	14
4	0.019	0.092	0.827	1
5	0.038	0.089	0.703	8
6	0.027	0.092	0.772	3
7	0.040	0.075	0.652	9
8	0.026	0.093	0.779	2
9	0.069	0.044	0.389	13
10	0.045	0.066	0.596	10
11	0.060	0.058	0.489	11
12	0.031	0.076	0.710	7
13	0.031	0.090	0.742	5
14	0.032	0.090	0.741	6
15	0.030	0.091	0.750	4

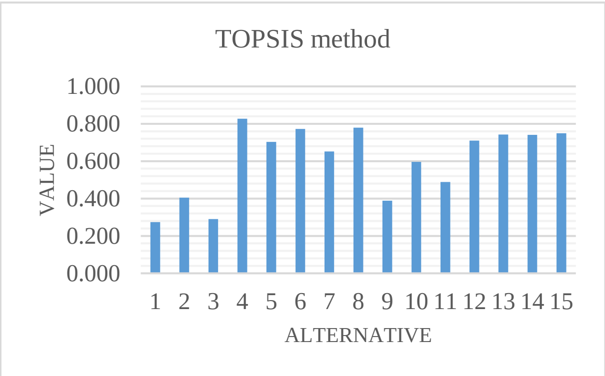

Fig 1. Ranking of the alternatives - TOPSIS method

The results of the application of the WASPAS method (λ=0.5) for the proposed MCDM model are represented in Table 5 and Fig. 2. From the results it can be concluded that the alternative with the best overall performance is alternative 4, while the second and third best ranked alternatives are, respectively, alternatives 6 and 8. The worst ranking alternative by the WASPAS method is alternative 1 while the second and third worst ranked alternatives are alternatives 3 and 9.

Table 5. Ranking of the alternatives - WASPAS method

Alternative	WSM	WPM	WASPAS	Rating
1	0.586	0.564	0.575	15
2	0.633	0.626	0.630	12
3	0.643	0.577	0.610	14
4	0.904	0.898	0.901	1
5	0.853	0.837	0.845	7
6	0.866	0.856	0.861	2
7	0.801	0.791	0.796	10
8	0.862	0.852	0.857	3
9	0.634	0.620	0.627	13
10	0.801	0.791	0.796	9
11	0.674	0.657	0.666	11
12	0.842	0.838	0.840	8
13	0.855	0.844	0.850	5
14	0.855	0.844	0.849	6
15	0.856	0.846	0.851	4

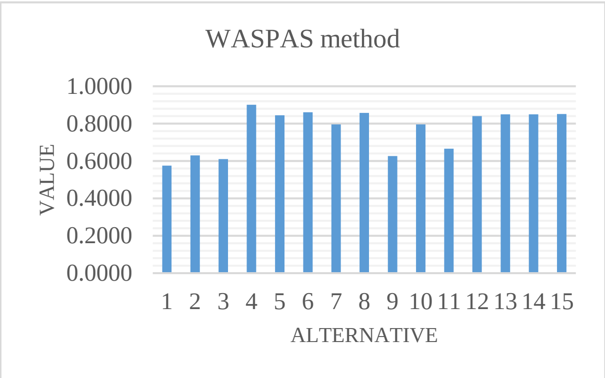

Fig 2. Ranking of the alternatives - WASPAS method

The results of the application of the EDAS method for the proposed MCDM model are represented in Table 6 and Fig. 3. From the results it can be concluded that the alternative with the best overall performance is alternative 4, while the second and third ranked alternatives are, respectively, alternatives 6 and 8. The worst ranking alternative by EDAS method is alternative 1, while the second and third worst alternatives are alternatives 2 and 9.

Table 6. Ranking of the alternatives - EDAS method

Alternative	NSPi	NSNi	ASi	Rating
1	0.092	0.000	0.046	15
2	0.000	0.290	0.145	14
3	0.415	0.089	0.252	11
4	1.000	0.953	0.977	1
5	0.614	0.900	0.757	8
6	0.686	0.934	0.810	2
7	0.295	0.888	0.591	10
8	0.711	0.904	0.807	3
9	0.017	0.282	0.150	13
10	0.641	0.720	0.681	9
11	0.000	0.480	0.240	12
12	0.631	0.918	0.774	4
13	0.522	0.996	0.759	6
14	0.516	0.999	0.757	7
15	0.555	0.982	0.769	5

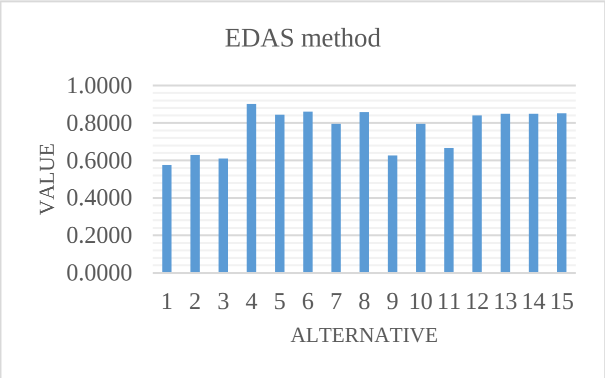

Fig 3. Ranking of the alternatives - EDAS method

From the ranking of the alternatives, for all three methods, it can be concluded that all methods ranked alternative 1 as the worst possible alternative, and alternative 4 as the best possible alternative. All methods also ranked alternative 9 as the third worst ranked alternative, while for the second worst ranked alternative, TOPSIS and WASPAS selected alternative 3, whereas EDAS selected alternative 2, while alternative 3 is ranked as the 4th worst alternative. There are also perturbances for the second and third best ranked alternative, WASPAS and EDAS ranked alternative 6 as the second and alternative 8 as the third best alternative, while the TOPSIS method ranked alternative 8 as the second and alternative 6 as the third best alternative. It can be seen that there are no bigger ranking differences between the applied MCDM methods, results are consistent for the best possible alternative and for the worst one. From the aspect of the technology, alternative 4 is selected as the best possible alternative because it has a reasonably high value of Cq and

Ce in combination with the highest achieved value of MRR. Cutting speed and focus position are recognized by many authors as the most influential parameters for the increase of MRR [42], [43]. In this case, alternative 4 has values of cutting speed and focus position on the highest levels, while the worst ranked alternative, i.e., alternative 1, has the values of cutting speed and focus position on the lowest levels. A common thing for both of these alternatives is the value of assist gas pressure on its medium value. So, it can be concluded that assist gas pressure is the least influential input parameter for the present case study in fiber laser cutting of S235 structural steel.

5. CONCLUSION

The focus of this study was on multi-criteria analysis of laser cutting process performances using three MCDM methods (TOPSIS, WASPAS and EDAS). Experimental investigation was conducted by using the Box-Behnken experimental design with 15 trials of which 3 were experimental trials in the central point. Trials of experimental investigation were considered as alternatives, while cut quality, material removal rate, kerf width, cutting efficiency and assist gas price were considered as assessment criteria. The TOPSIS, WASPAS and EDAS methods were successfully used to rank the alternatives, while relative importances of the criteria were determined by using a pair-wise comparison matrix and the geometric mean method of the AHP method. Experimental investigation and the use of TOPSIS, WASPAS and EDAS suggested that the cutting conditions obtained in experimental trials 4, 6 and 8 are the most preferred ones, while cutting conditions obtained in experimental trials 1, 3 and 9 are the least preferred ones. Conducted experimental trials allowed one to conclude that for the present laser cutting MCDM model higher values of cutting speed are preferred while assist gas pressure has a small influence on the overall ranking of the alternatives. Smaller values of cutting speed led to the least preferred alternatives. Complex problems which appear in modern manufacturing society are often assessed based on a large number of criteria which are often of conflicting natures. In these situations, the MCDM approach offers a receptive methodology which can be helpful in the determination of the best possible alternatives.

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