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Traditional and Integrated MCDM Approaches for Assessment and Ranking of Laser Cutting Conditions

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ABSTRACT

Multiple benefits and advantages that offer laser cutting technology are difficult to achieve if the laser cutting parameter conditions are not adequately set. Determining laser cutting conditions is not trivial task considering large number of controllable inputs, existence of multiple process performances which are often mutually opposed as well as effects of noise factors. Different scientific methods and engineering approaches represent more sophisticated approaches which aid assessment and determination of the most favourable (optimized) cutting conditions. This study is focused assessment and ranking of laser cutting conditions in CO_2 laser cutting of AISI 316L stainless steel. Based on kerf width and surface roughness experimental data and estimation of material removal rate (MRR) and total variable costs, four criteria in the multi-criteria decision making (MCDM) model were considered. For solving the developed model, six well-known MCDM methods were applied, and in addition, in order to overcome ranking inconsistency, robust decision-making rule was developed upon which final ranking was obtained.

1. Introduction

Laser cutting is a complex, multifactorial process where removal of material is achieved by high power and energy densities which cause immediate melting and/or evaporation of material. To achieve several advantages of this non-conventional technology, such as accuracy, precision, good productivity along with high cut quality, production flexibility, no tool wear etc. [1], the determination of laser regimes is extremely important, considering that many quality, productivity and cost criteria are generally mutually conflicting goals [2].

In production practice, acceptable cutting regimes from the aspect of a larger number of criteria are most simply achieved by applying manufacturers' recommendation, accumulated knowledge, experience, iterative one factor at a time (OFAT) or trial-and-error experimental strategies. More sophisticated approaches that are often promoted in the literature for handling multiple criteria, and actually assure determining of more favorable cutting conditions with less resources, include

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integrated model-based approach, hybridization of Taguchi method and grey rational analysis (GRA), principal component analysis (PCA), utility concept (UC), and other methods for handling multiple criteria.

An integrated approach based on the use of artificial neural network (ANN) and non-dominated sorting genetic algorithm (NSGA-II) was applied by Ding et al. [3] for multi-objective fiber laser cutting optimization with respect to kerf width and surface roughness. Huang et al. [4] proposed also integrative model (ANN-NSGA-II) for optimization of three cut quality characteristics, i.e., surface roughness, kerf width and kerf taper. Kechagias et al. [5] applied Box-Behnken design and response surface methodology (RSM) for multi-objective optimization of cut geometry, surface texture and surface roughness in CO_2 laser cutting of acrylonitrile styrene acrylate (ASA) 3D-printed plates. Rajamani and Tamilarasan [6] optimized Nd:YAG laser process parameters with respect to kerf deviation and MRR using NSGA-II. Dehkordi et al. [7] used ANN model and particle swarm optimization (PSO) metaheuristic algorithm to optimize parameters in fiber laser cutting of Inconel 600 considering kerf width and surface roughness as objective functions. Vora et al. [8] applied heat transfer search algorithm to determine Pareto set of alternative cutting regimes in fiber laser cutting of Ti6Al4V with respect to kerf width, surface roughness, MRR and burr height. A metaheuristic-based process optimization was proposed by Ürgün et al. [9] to simultaneously optimize the kerf width and depth in CO_2 laser cutting of polymethylmethacrylate (PMMA) sheets. Solving multi-objective process parameter optimization problems in nonconventional machining, including laser cutting technology, with the use of multi-objective Jaya (MO-Jaya) algorithm was discussed by Venkata Rao et al. [10]. Laser cutting multi-objective optimization of performances was usually accomplished with hybrid Taguchi-GRA approach. Begic-Hajdarevic et al. [11] applied this approach for determining laser cutting conditions with respect to kerf width and surface roughness in CO_2 laser cutting of aluminum alloy AlMg3. Turkkan et al. [12] optimized process parameters with respect to kerf width and surface roughness in fiber laser cutting of AISI 304L stainless steel. The same methodology was used by Senthilkumar et al. [13] to determine process parameter settings with respect to hardness, MRR and kerf width in CO_2 laser cutting of AISI 304 stainless steel.

In addition to the previously discussed approaches, assessment, ranking and selection of laser cutting regimes may be tackled within the multiple-criteria decision-making (MCDM) framework where the goal would be to assess and rank multiple pre-known alternative cutting conditions with respect to different criteria of variable significance [14]. In spite of a large number of MCDM methods their application in non-conventional machining is quite limited [15-18], in contrast to traditional machining processes such as drilling, turning and milling processes [19].

In this paper assessment and ranking of laser cutting conditions was attempted using two approaches, i.e., traditional and integrated MCDM approaches. Traditional approach applied six well-known MCDM methods for generation of decision making rule. Based on kerf width and surface roughness experimental data and estimation of material removal rate (MRR) and total variable costs, the CO_2 laser cutting MCDM model was developed considering nine laser cutting conditions. In addition, to resolve the issue of ranking inconsistency, the application of robust decision-making rule [20], as an integrated MCDM approach, was proposed.

2. Experimental setup and MCDM model

In this paper, a synthesis of the experimental results of CO_2 laser cutting of AISI 316L stainless steel was performed. In the experiment the laser power was set at constant level (3.2 kW), focusing plane at -2 mm, while coaxially supplying nitrogen (5.0) in the kerf using nozzle with diameter of 1.5 mm. Variable factors, which were used to define alternatives, included cutting speed (v) and nitrogen pressure (*p*). According to the 3^2 factorial design, nine alternative cutting regimes were defined: A1 (v = 6 m/min, p = 10 bar), A2 (v = 2 m/min, p = 10 bar), A3 (v = 6 m/min, p = 14 bar), A4 (v = 2 m/min, p = 14 bar), A5 (v = 6 m/min, p = 12 bar), A6 (v = 2 m/min, p = 12 bar), A7 (v = 3 m/min, p = 10 bar), A8 (v = 3 m/min, p = 14 bar), and A9 (v = 3 m/min, p = 12 bar). All cutting regimes were performed at the same CO_2 laser cutting machine (Figure 1) in unaltered processing conditions.

Fig. 1. CO_2 laser cutting machine used in experimentation (Prima Industrie Domino)

Laser cutting results were evaluated based on cut quality characteristics (kerf width - K_w, arithmetic mean roughness - R_a), productivity (volumetric material removal rate - MRR) and cost (total variable cost - C_v) criteria. Marsurf XR 1 surface roughness tester was used for roughness measurements while DeMeet 443 optical CMM was used for kerf width measurements. The material removal rate and total variable cost were estimated based on mathematical models [21]. Based on performed experimental plan, measured and estimated criteria attribute values, the following CO_2 laser cutting decision matrix was proposed (Table 1).

Table 1
CO_2 laser cutting decision matrix (model)

Alternative	K_w (mm)	R_a (μm)	MRR (mm^3/min)	C_v (EUR/m)
A1	0.245	2.119	2935.60	0.112
A2	0.289	1.294	1157.67	0.337
A3	0.245	1.390	2943.60	0.159
A4	0.296	1.180	1185.40	0.44
A5	0.247	2.082	2969.60	0.136
A6	0.288	1.446	1153.20	0.407
A7	0.291	1.122	1748.30	0.225
A8	0.280	1.157	1680.40	0.317
A9	0.258	1.036	1549.80	0.271

In the proposed decision matrix, except MRR, all considered criteria are minimization criteria, whereby it is understood that they do not have the same importance. Their relative significance, represented via criteria weights, was estimated based on expert opinions using AHP method [22] as shown in Table 2. For the given random index of 0.89, consistency ratio of 0.043 was calculated. Therefore, one can argue that there were no contradictions in the judgments made in pairwise comparison of considered criteria.

Table 2
Criteria weights in the present study

Criterion	K_w	R_a	MRR	C_v
Criterion weight	0.067	0.207	0.158	0.568

3. Applied MCDM approaches

In the present study for solving the proposed laser cutting decision matrix (model) two approaches were attempted, i.e., traditional and integrated (Figure 2). As could be seen the entire methodological framework for assessment, ranking and selection of laser cutting conditions consists of three main steps (S_1, S_2 and S_3). In the first step (S_1) based on laser cutting data obtained experimentally each alternative cutting conditions is assigned with appropriate attribute values for each criterion (process performance characteristic). For a given case study and/or specific production requirements, decision maker determines the relative significance of the considered performance (criteria) by estimating the criteria weights. In the second step (S_2) thus created laser cutting decision matrix is solved by applying different decision making rules of multiple MCDM methods. In the present study six MCDM methods were applied, i.e., Additive Ratio ASsessment (ARAS), VIšeKriterijumska Optimizacija i kompromisno Rešenje (VIKOR), COmplex PRoportional ASsessment (COPRAS), Technique for the Order Preference by Similarity to Ideal Solution (TOPSIS), Multi-Objective Optimization by Ratio Analysis (MOORA) and Weighted Aggregated Sum Product ASsessment (WASPAS). Based on the application of six decision making rules six complete ranking lists are obtained which are compared and analyzed in Step 3. If there is a strong agreement (consensus) regarding the ranking of alternatives as determined by different MCDM methods, analysis and selection of particular laser cutting conditions would be final instance in the proposed methodological framework. Otherwise, if certain/significant ranking inconsistency exists, application of integrated MCDM approach based on the use robust decision-making rule (RDMR) for determining the final rankings was proposed [20].

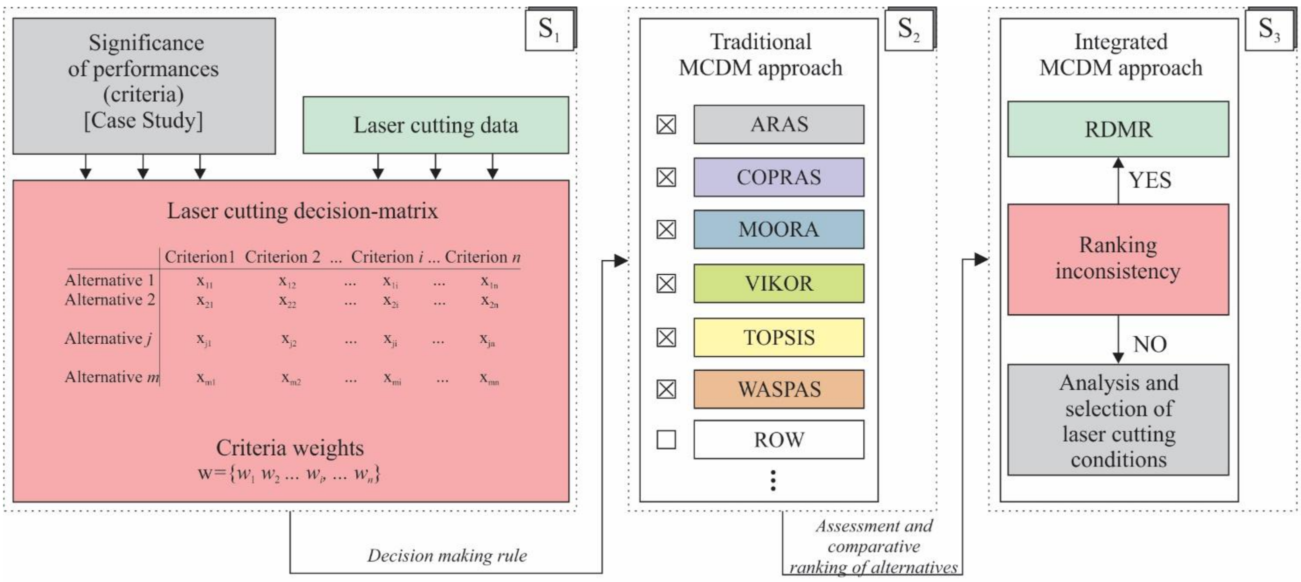

Fig. 2. Applied traditional and integrated MCDM approaches

3. Results and analysis

Initially, the developed CO_2 laser cutting decision matrix was solved using a traditional approach by applying six MCDM methods i.e., ARAS, VIKOR, COPRAS, TOPSIS, MOORA and WASPAS. Based on calculated utility values, the complete rankings of alternatives were obtained as given in Table 3.

Table 3
Complete ranking of alternatives using six MCDM methods

Alternative	ARAS	COPRAS	MOORA	VIKOR	TOPSIS	WASPAS
A1	1	2	2	1	2	1
A2	7	7	7	7	7	7
A3	3	1	1	3	1	3
A4	8	9	9	8	8	8
A5	2	3	3	2	3	2
A6	9	8	8	9	9	9
A7	4	4	4	4	4	4
A8	6	6	6	6	6	6
A9	5	5	5	5	5	5

As could be observed from Table 3, ARAS, VIKOR and WASPAS have complete overlap of alternative rankings, which also applies to rankings of COPRAS and MOORA, whereby the ranking list determined by the TOPSIS method is almost identical to those of COPRAS and MOORA as it differs only in relation to the ranking of the least preferred alternative. Mismatch of alternative rankings is not unusual when solving decision making problems using different decision-making rules [23, 24]. Ranking list mismatch may arise from specific properties of different MCDM such as determination of the best/worst solution, specific hyper-parameters, formulae used for normalization of attribute values, etc. [25]. When different MCDM methods are applied and ranking inconsistency is observed, the rationality and objectivity of the decision-making process is affected [26]. One can argue that with an increase in the number of applied MCDM methods as well as complexity of the decision making problem, the issue of inconsistent ranking would be more pronounced.

Since it is impossible to say which method is the best choice for a particular problem [27], and the fact that in the present case study there are strictly divided results regarding the three first-placed alternatives, the robust decision-making rule (RDMR) was derived for determining the final ranking of alternative cutting conditions. The basic idea of RDMR is to rank alternatives using signal to noise rations estimated using utility function values of each applied MCDM method [20].

The rankings of laser cutting conditions after application of the RDMR are given in Figure 3.

As can be seen from the results, the first, second and third ranked alternatives are A1, A3 and A5, i.e., all cutting regimes in which the cutting speed is at the highest level, irrespective of nitrogen pressure. This could be expected given that this parameter directly affects the most significant criterion, total variable costs and in addition MRR. Accordingly, the least preferred alternative is alternative A6, i.e., the laser cutting condition with the lowest cutting speed and intermediate nitrogen pressure (v = 2 m/min, p = 12 bar). By analyzing alternative cutting conditions and their ranking in Figure 3, it could be revealed that increasing nitrogen pressure negatively affects ranking position. This is due to the direct relationship of nitrogen pressure and assist gas flow rate and associated variable costs. In sum, one may argue that an increase in the cutting speed improves the ranking, whereas the effect of the nitrogen pressure is opposite and in quantitative sense less pronounced.

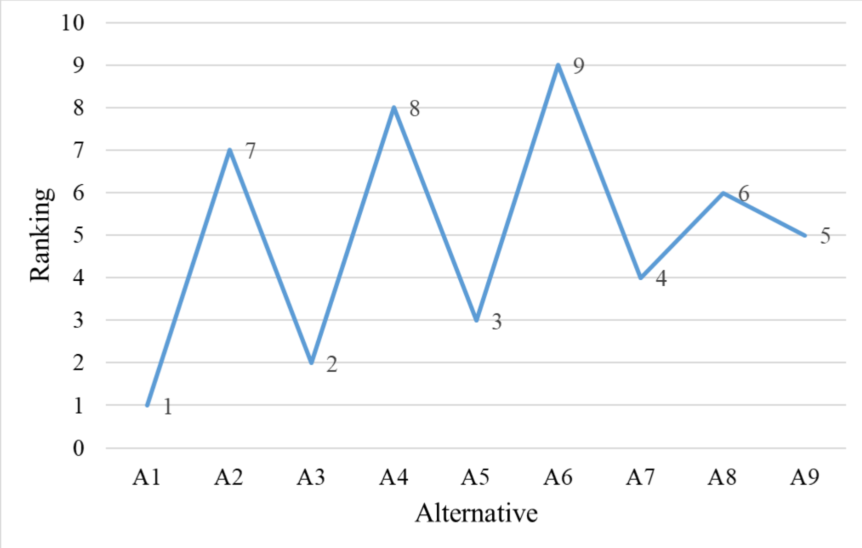

Fig. 3. Ranking of laser cutting conditions by RDMR

5. Conclusions

Assessment, ranking and selection of the most appropriate cutting regimes is of utmost importance in laser cutting given the existence of multiple process performances, their different significance and mutual antagonism. In that regard, a laser cutting MCDM model for assessment and ranking of different laser cutting conditions with respect to four criteria in CO_2 laser cutting of AISI 316L stainless steel. In this paper assessment and ranking of laser cutting conditions was attempted using two approaches, i.e., traditional and integrated MCDM approaches. Based on estimated criteria weights, applied MCDM methods, the following conclusions can be stated:

- When applied to the same laser decision matrix application of different MCDM methods may result in different ranking which may affect indecisiveness. In this study ARAS, VIKOR and WASPAS methods showed complete ranking consistency, but this was not the case with the other MCDM methods.
- The application of the robust decision-making rule makes decision making process more objective and robust.
- Within the covered experimental space and considered criteria with associated significance it was observed that the cutting speed is the most important parameter affecting the final ranking.
- Increasing the nitrogen pressure worsens the ranking of given alternative, but the influence of nitrogen pressure on the ranking is less pronounced in comparison with the effect of the cutting speed.
- Analysis of the effects of process parameters. which define alternative laser cutting conditions, based on robust decision-making rule creates a general impression of the significance and qualitative nature of the involved parameters.

The presented methodology which made use of robust decision-making rule may be receptive approach for resolving ranking inconsistency which may occur when solving laser cutting MCDM problems. Within the proposed methodological framework for assessment, ranking and selection of laser cutting conditions, the decision makers (process planners) can alter criteria weights to accommodate different production requirements and needs. In addition, the use of additional MCDM methods and sensitivity analysis can make the applied approach even more robust and objective.

Author Contributions

Conceptualization, M.M., G.P. and D.P.; methodology, M.M., G.P. and D.P.; software, M.M., G.P. and P.J.; validation, G.P. and D.P.; formal analysis, M.M., G.P., D.P. and P.J.; investigation, M.M. and P.J.; resources, M.M. and P.J.; data curation, M.M., G.P. and P.J.; writing—original draft preparation, M.M. and G.P.; writing—review and editing, M.M., G.P., D.P. and P.J.; visualization, M.M. and P.J.; supervision, M.M.; project administration, M.M.; funding acquisition, M.M., G.P., D.P. and P.J. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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