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SELECTION OF LASER CUTTING SYSTEMS USING MCDM METHODS

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Abstract

Due to highly competitive global market, the manufacturing companies need a systematical approach for appropriate selection of laser cutting systems. Evaluation and selection of a laser cutting system involves multiple conflicting criteria, thus represents a complex multi-criteria decision making (MCDM) problem. In this paper, to tackle the difficulty of the laser cutting system selection, a MCDM model is proposed while two preference ranking-based MCDM methods, i.e. complex proportional assessment (COPRAS) and operational competitiveness ratings analysis (OCRA), were used for selection of the most appropriate laser cutting system. In order to determine the relative significance of considered criteria a pair-wise comparison matrix of the analytic hierarchy process was used. The obtained ranking performances of these methods are compared with the rankings of the technique for order preference by similarity to ideal solution (TOPSIS) and VIšeKriterijumska Optimizacija i Kompromisno Rešenje (VIKOR) methods.

***Key words**: Laser cutting systems, multiple-criteria decision making, COPRAS, OCRA*

1 INTRODUCTION

Sheet metal cutting has since become the dominant industrial use of lasers in material processing. Laser cutting machines are used for precise contour cutting of thin sheets. Nowadays, various types and construction of laser cutting machines can be met in industrial applications. For 2-D contour cutting laser cutting machines with X-Y coordinate table are effective and economical.

Lasers can be generally classified by their wavelength and by the amount of power in the output beam. Among various types of lasers, in manufacturing operations for metal cutting, the most common are CO_2 laser, fiber laser and Nd:YAG lasers. These lasers provide the most cost effective tool for most metal cutting applications. The basic differences between the Nd:YAG, fiber and CO_2 lasers is the wavelength of the beam that it produces. The light of the Nd:YAG (1.06 μm) and fiber lasers (1.07 μm) are emitted at a wavelength that is precisely 10 times smaller than that of a CO_2 laser (10.6 μm). This smaller wavelength also means that if the Nd:YAG/fiber and CO_2 lasers were used in the same application, the Nd:YAG/fiber would have a much smaller spot size [1].

Laser cutting is achieved by focusing the laser beam to a sufficiently small spot diameter so as to achieve the necessary power density to melt and vaporize the workpiece material. For the best results, steel cutting typically requires a power density of 10^7 to 10^8 W/cm^2. The focused beam of even a 2 kW fiber laser demonstrates a 5 times greater power density at the focal point when compared with a 4 kW CO_2 laser. Light of fiber laser possesses a 2.5 times greater absorption characteristic due to the shorter wavelength. Because the light of fiber laser and Nd:YAG laser is more easily absorbed by metal surfaces, it can be used for work on highly reflective materials, such as copper or silver alloys [2].

Selection of proper laser cutting system (machine) is of prime importance for manufacturers in order to achieve high competitiveness on the market. Making right decisions means increased productivity, product quality, increased product flexibility and cost savings. On the other hand, improperly selected machine tool can negatively affect the overall performance of a manufacturing system and the responsive manufacturing capabilities of a company [3, 4].

Evaluation and selection of a laser cutting system is a complex decision making problem involving multiple conflicting criteria, such as investment cost, laser power, wavelength, maximal material thickness, operational cost, etc. Thus the selection problem is a time-consuming and difficult decision making problem requiring advanced knowledge and domain experience. A detailed and thorough analysis is needed before an investment decision is made. In that sense, this paper presents a logical and systematic procedure by applying different MCDM methods to evaluate competitive laser cutting systems, including CO_2 laser, fiber laser and Nd:YAG laser. An attempt is made to explore the applicability and capability of two MCDM methods, i.e. COPRAS and OCRA methods. In order to validate the obtained complete rankings of COPRAS and OCRA methods, the laser cutting system selection problem is solved using TOPSIS and VIKOR methods. The similarity of rank output resulting from different MCDM methods is assessed using rank correlation coefficients.

2 DEFINITION OF THE DECISION MATRIX

Selection of the most important criteria allows objective comparison between the competitive alternatives. Determination of the criteria for the considered decision making problem was done via questionnaires and interviews with machining specialists and engineers from manufacturing companies which made use of laser cutting technology and by making use of the catalogues published by laser cutting systems manufacturers. The present decision making problem considers the following 7 criteria influencing the laser cutting system selection problem:

- Laser power: Laser power is one of the most important characteristic by which a given laser cutting system is evaluated. Increase in laser power generates conditions for increase in maximal cutting speeds i.e. increase in material removal rate as well as cutting thicker materials.
- Wavelength: The wavelength of the laser radiation influences the ability of a material to absorb laser radiation.

The smaller the wavelength of the laser radiation is, the higher is absorptivity and hence most of materials better absorb YAG and fiber laser radiation than CO_2 laser. Steel reflects about 93% of the laser light emitting at a wavelength of 10 μm. On the other hand, only 75% of the laser light at 1 μm wavelength is reflected. Since a laser may operate at only one wavelength, it is considered to be invariant, constant factor of the laser cutting process. When purchasing a laser cutting system, with specific manufacturing requirements, the wavelength of the laser radiation should be considered.

- Power consumption: It is related to the power consumption of the laser cutting system in kW/h. The power consumption of a laser cutting system depends on the laser output power and process parameter settings. This will depend on the type of laser and suitability of laser cutting system to cut a given workpiece material.
- Investment cost: This criterion is concerned with the initial investment and setup cost needed to install a given laser cutting system. The investment cost is in direct relation with laser power, characteristics of coordinate the X–Y table and quality of CNC control unit. However, investment cost may vary considerably, depending on the technical requirements, even if the size of work area is the same.
- Maximal material thickness: The applicability of a given laser cutting system with respect to the most widely used materials in industry is taken care of under this criterion. It determines the maximal material thickness in mm that can be cut by a given laser cutting system. This criterion is of prime importance for manufacturers as it determines the range of application, hence it will have a major role in the selection of the most suitable laser cutting system.
- Position accuracy: Accurate positioning of the workpiece on the X–Y table with defined direction of cut can be easily obtained during laser cutting thus facilitating the machining of flimsy and flexible materials. Positioning accuracy is determined by the characteristics of the CNC control unit.
- Hourly operating cost: Manufacturers using laser cutting technology are interested in calculating hourly operating cost and on this basis are trying to evaluate profitability of a given machining application. Hourly operating cost includes expenses related to fixed and variable hourly costs of machining, equipment, gas consumption, etc. It should be noted that hourly operating cost vary considerably with workpiece material and required quality.

Among the considered criteria, laser power (LP) and maximal material thickness (MMT) are beneficial criteria where higher atributive values are desirable, and on the other hand, wavelength (W), power consumption (PC), investment cost (IC), positioning accuracy (PA) and hourly operating cost (HOP) are non-beneficial criteria where smaller atributive values are preferable.
The considered criteria and the alternatives with their quantitative data are given in Table 1. The quantitative atributive data of alternatives were obtained from the catalogues published by laser cutting systems manufacturers.

3 APPLIED MCDM METHODS

As could be seen from Table 1 none of the competitive laser cutting systems meets all of set goals simultaneously. Therefore, for manufacturers using laser cutting technology it is of practical importance to evaluate and rank competitive laser cutting systems. In that sense application of MCDM methods, i.e. COPRAS and OCRA, is intended to aid MCDM process in terms of preferred requirements.
The preference ranking method of complex proportional assessment (COPRAS) method was developed by Zavadskas et al. [5]. In this method, the influence of beneficial and non-beneficial criteria on the evaluation result is considered separately. The selection of the best alternative is based considering both the ideal and the anti-ideal solutions. The main procedure of COPRAS method includes several steps and it discussed and illustrated in [6].
Operational competitiveness ratings analysis (OCRA) is a MCDM method which can be used to calculate relative performance of a set of competitive alternatives. OCRA method uses an intuitive approach for incorporating the decision maker’s preferences about the relative importance of the criteria [7]. The main advantage of OCRA method is that it can deal with those MCDM situations when the relative weights of the criteria are dependent on the alternatives and different weight distributions are assigned to the criteria for different alternatives as well as some of the criteria are not applicable to all the alternatives [8]. The main procedure of OCRA method consists of several steps as given in [8, 9].

Table 1 Developed decision matrix

Laser cutting system (LCS)	LP (kW)	W (μm)	PC (kW/h)	IC (EUR)	MMT (mm)			PA (mm)	HOC (EUR)
					Mild steel	Stainless steel	Aluminum		
Goal	Max	Min	Min	Min	Max	Max	Max	Min	Min
Nd:YAG LCS	0.6	1.06	20	98000	8	5	0.5	0.02	3.2
CO_2 LCS 1	3.5	10.6	55	398000	20	12	6	0.03	3.6
CO_2 LCS 2	4	10.6	67	460000	20	15	10	0.1	4
CO_2 LCS 3	4.4	10.6	51	560000	25	12	12	0.01	4.4
Fiber LCS 1	2	1.07	8	399000	15	6	5	0.05	2.1
Fiber LCS 2	3	1.07	12	410000	18	10	8	0.05	2.2
Fiber LCS 3	4	1.07	16	419000	25	12	10	0.05	2.3

4 RESULTS AND DISCUSSION

In this COPRAS and OCRA methods were applied for solving laser cutting system selection problem. Also the use of AHP method for determining of criteria weights was discussed. The obtained ranking of the competitive laser cutting systems were compared with the ones obtained by applying VIKOR and TOPSIS methods, as one of the most popular and widely applied classical MCDM methods.

At first, estimations of the relative importance of considered criteria are derived using the pair-wise comparison matrix of the AHP. The Saaty nine-point preference scale [10], which has reflexive property between the relatedness of two criteria, is adopted for constructing the pair-wise comparison matrix based on the experience of the authors (Table 2). Once the pair-wise comparison matrix of criteria is developed, using the normalization of the geometric mean method, the criteria weights are obtained as w_j = [0.08, 0.02, 0.08, 0.14, 0.2, 0.2, 0.2, 0.02, 0.08]. Ability of laser cutting system to be used for cutting thicker materials and investment cost are the most important criteria, while wavelength and positioning accuracy are the least important ones as expected from pair-wise comparison process.

To ensure consistency in the pair-wise comparison matrix and the accuracy of obtained criteria weights, a consistency check is performed. For random index of 1.45, consistency index and ratio values of 0.098 and 0.06 were obtained, respectively. These values show that there are no contradictions in the judgments and that the evaluation of the relative importance of the criteria is reasonable and reliable.

Once the criteria weigths have been determined one can easily obtain the final rankings of alternatives, i.e., competitive laser cutting systems, by using the well known computation procedure of each considered MCDM method.

In order to validate the obtained complete rankings of COPRAS and OCRA methods, the same laser cutting system selection problem is solved using TOPSIS and VIKOR methods. The computational details of TOPSIS and VIKOR methods are not shown here because of space limitations. The main step-by-step procedure of these is explained in detail in [6, 11]. Table 3 shows the complete rankings of all competitive laser cutting systems derived using four MCDM methods.

Table 2 The pair-wise comparison matrix of criteria

		LP	W	PC	IC	MMC			PA	HOC
						Mild steel	Stainless steel	Aluminum		
LP		1	9	3	0.5	0.2	0.2	0.2	5	1
W		0.11	1	0.2	0.14	0.14	0.14	0.14	1	0.14
PC		0.33	5	1	1	0.33	0.33	0.33	7	3
IC		2	7	1	1	1	1	1	9	1
MMC	Mild steel	5	7	3	1	1	1	1	9	3
	Stainless steel	5	7	3	1	1	1	1	9	3
	Aluminum	5	7	3	1	1	1	1	9	3
PA		0.2	1	0.14	0.11	0.11	0.11	0.11	1	0.14
HOC		1	7	0.33	1	0.33	0.33	0.33	7	1

Table 3 Complete rankings of laser cutting systems

Laser cutting system	COPRAS	OCRA	TOPSIS	VIKOR
Nd:YAG LCS	7	7	7	7
CO_2 LCS 1	5	5	5	5
CO_2 LCS 2	3	3	3	3
CO_2 LCS 3	2	1	2	2
Fiber LCS 1	6	6	6	6
Fiber LCS 2	4	4	4	4
Fiber LCS 3	1	2	1	1

As could be seen from Table 3, three out of four MCDM methods proposed Fiber LCS 3 as the most appropriate laser cutting system. It is observed that the worst choice remains to be Nd:YAG LCS. Table 3 also exhibit a substantial agreement between the intermediate rankings of the competitive laser cutting systems.

It is interesting to note that between different MCDM methods actually there exists only very small difference in the ranking of the fourth alternative.

In order to compare the complete rankings of two sets, Spearman's rank correlation coefficient can be used. Its values are between –1 and +1, where the value of +1 indicates a perfect match between two rank orders.

It is also well validated in Table 4 where the Spearman's rank correlation coefficients between the rankings obtained using different MCDM methods are given.

Table 4 Spearman's rank correlation coefficient values

	OCRA	COPRAS	VIKOR	TOPSIS
OCRA	-	0.964286	0.964286	0.964286
COPRAS	-	-	1	1
VIKOR	-	-	-	1
TOPSIS	-	-	-	-

From Table 4 it is observed that there exist excellent Spearman's rank correlation coefficients between the rankings obtained using the four MCDM methods. It is found that there exists very high correlation between different MCDM methods, perfect correlation between TOPSIS and VIKOR methods and the coefficients between OCRA and other methods is somewhat lower than those of other pairs. It is interesting to note that the performance of COPRAS method is exactly the same to that of VIKOR and TOPSIS methods.

In the case where due to techno-technological, economical or other reasons selection of top rated laser cutting system is not viable, the other top rated laser cutting systems can be used. CO_2 LCS 3 and CO_2 LCS 2 are the other best laser cutting systems, with the second and third rank, respectively.

5 CONCLUSIONS

The presence of a number of available laser cutting systems has brought out the idea of selecting the most suitable laser cutting system by considering their unique process characteristics as well as investment and operational costs. As laser cutting systems selection is often difficult and time consuming, there is a need for a structured approach in order to facilitate the decision making process.

In this study, a MCDM model is proposed to assist decision makers in the selection of the most appropriate laser cutting system. Most of the required data for the study is obtained via questionnaires given to experts and catalogues published by laser cutting systems manufacturers. A pair-wise comparison matrix of the AHP method was used to determine the relative significance of considered criteria, and then the competitive laser cutting systems were ranked by applying COPRAS and OCRA methods.

The obtained results suggested that Fiber LCS 3 is the most appropriate alternative, while Nd:YAG LCS is the lowest graded alternative. Besides the conducted analysis it should be noted that fiber laser cutting systems are generally maintenance-free and feature a long service life which enables significant maintenance cost savings. Fiber laser's good energy efficiency means very low power consumption, i.e. operational cost savings. Since fiber laser use diode as a light source and optical fiber as a transmission medium, there is no loss of energy transmitted to the laser cutting head and this can be regarded as one of the most important advantages over the other laser cutting systems.

Finally it should be noted that regardless of the selected laser cutting system, the selection of the (near) optimal set of process parameter values is essential for achieving multiple performance characteristics in the actual cutting process.

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