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A new hybrid decision-making strategy of cutting fluid selection for manufacturing environment

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Abstract. Today, for a manufacturing environment, the choice of cutting fluids is vital. The desired cutting fluid provides excellent surface quality and better tool life. In this research, a new decision support system was proposed to select different cutting fluids in the manufacturing environment. In this context, three studies were taken from the literature. Fifteen different multi-criteria decision-making techniques and four normalization methods were used to determine the best conditions for these studies. In terms of weighting criteria, a new hybrid criteria weighting method was proposed. The obtained rankings were compared with the Spearman correlation test. Compared to the literature results, the proposed strategy produced consistent results in terms of rankings ($p < 0.05$).

Keywords. Multi-criteria decision making (MCDM); manufacturing; decision support system; cutting fluid selection; tool life.

1. Introduction

In the traditional method, the choice of coolants depends on functional requirements, quality and cost. The use of coolants creates intense financial problems for manufacturing companies since the laws and directives regulating industrial/environmental safety increase. The manufacturing industry uses a variety of fluids for cutting and lubricating. The coolant also provides excellent surface quality and better tool life. For machining operations, friction phenomena cause heat generation. The generated heat's impact increases tool wear/surface roughness and decreases the workpiece's dimensional accuracy [1]. Therefore, optimum coolant selection is crucial because it minimizes environmental hazards, costs and increases the machining operation's efficiency [2, 3].

In previous studies, several authors studied the effects of the application of different coolants [4–8]. Axinte *et al* [4] compared six different coolants for the turning process when comparing tool life. Sales *et al* [5] examined the advantages and disadvantages of applying coolants. Soković and Mijanović [6] examined the environmental impact of coolants and their effects on machinability. De Chiffre and Belluco [7] have studied the use of coolants in different material removal operations. Cakir *et al* [1] investigated different cutting fluids applications for different workpiece materials and cutting tool materials. Jayal and Balaji [8] investigated the impact of various coolant processes on tool wear.

The choice of cutting coolant is generally considered as a multi-criteria decision-making (MCDM) problem. In the previous studies, authors have used many MCDM methods to choose suitable cutting fluids for material removal operations [9–21]. Sutherland *et al* [9] proposed an internet-based coolant assessment program (CFEST) that can give coolants' details in terms of cost, safety, etc. Sun *et al* [10] determined grinding fluids' performance when using a two-grade fuzzy synthetic decision-making system using Analytical Hierarchy Process (AHP). Rao and Gandhi [11] developed a method via digraph and matrix approach to select optimum coolant. Tan *et al* [12] proposed a multi-purpose decision-making approach for the choice of coolants. Meciarova and Stanovsky [3] proposed a program for optimizing the coolant choosing procedure based on environmental impact/human safety. Abhang and Hameedullah [13] used the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and AHP methods to choose a suitable lubricant. Kumar and Prasad [14] used the Chi-square statistics and matrix method to solve the coolant selection problem. Chakraborty and Zavadskas [15] used the weighted aggregated sum product assessment (WASPAS) technique for the selection of coolant. Jagadish and Ray [16] have chosen the optimum cutting fluid considering environmental hazards/cost and quality. AHP/VIKOR hybrid criteria decision-making method was used in their study. Jagadish and Ray [17] used multi-purpose optimization on the basis of simple ratio analysis (MOOSRA) technique to select the best coolant to minimize environmental hazard/cost and

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increase surface quality. Tiwari and Sharma [18] used Simple Additive Weighting (SAW) and weighted product model (WPM) to rank various vegetable-based coolant options. Prasad and Chakraborty [19] proposed a quality function deployment (QFD)-based technique for the selection of coolants. Makhesana and Patel [20] studied the choice of solid lubricant-assisted lubrication strategy using PROMETHEE method. Rao and Patel [21] used the Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE) preference ranking method to select coolant using both crisp and fuzzy criteria values. According to the literature review, it has been found that the selection of an optimum cutting fluid is vital in the manufacturing industry and several techniques have been developed to evaluate this decision-making problem related to cutting fluid selection. According to the literature studies, it is also seen that software or MCDM models have been developed for the selection of coolants. Although different MCDM models were used, these different models were not compared to each other. In MCDM models, there are many model parameters, many normalization techniques and different weighting methods and these characteristics change the results. Therefore, it is essential to solve the same problem with several different MCDM models and observe the change of results. To the best of our knowledge, no such detailed research on the selection of cutting fluids has been found before in terms of the literature studies. Besides, the ranking results have not been examined in detail in terms of frequency. Also, criteria weights were not evaluated objectively and subjectively at the same time in this topic.

This study proposes cutting fluid selection with a new approach to eliminate the dependence of the results on MCDM methods by using many decision-making, normalization, and criteria weighting methods. In addition, it is aimed to overcome the disadvantages by hybridizing the criteria weights with subjective and objective methods. In this study, fifteen different MCDM models and three cutting fluid selection problems were evaluated and the results were compared. Each decision-making model was evaluated using four different normalization techniques. In addition to the weights previously determined in the literature, the results were compared using Entropy weighting method. In the second part of the study, the methods used are explained. Section 3 describes the case studies used. Then the results were given in section 4 and the conclusions are provided in section 5.

2. Methodology

In the study, four different normalization methods and fifteen different MCDM techniques were used to select different cutting fluids. The details of the methods are given below.

2.1 *Normalization methods*

The equations for different normalization methods and the symbols used in these equations are given below [22].

i= the number of alternatives

j= the number of criteria

x_{ij}= the normalized value for the jth criteria of ith alternative

a_{ij}= the values for jth criteria of ith alternative

Max. weighting formula is given below (Eq. 1).

$$x_{ij} = \frac{a_{ij}}{a_j^{max}} \text{ for benefit} \tag{1}$$

Sum weighting formula is given below (Eq. 2).

$$x_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \text{ for benefit} \tag{2}$$

Max-min weighting formula is given below (Eq. 3).

$$x_{ij} = \frac{a_{ij} - a_j^{min}}{a_j^{max} - a_j^{min}} \text{ for benefit} \tag{3}$$

Vector weighting formula is given below (Eq. 4).

$$x_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{n} a_{ij}^2}} \text{ for benefit} \tag{4}$$

2.2 *Multi-criteria decision making (MCDM) techniques*

Several MCDM methods were used in this study. These methods are explained briefly.

2.2a *SAW (simple additive weighting)*: SAW is an MCDM approach that includes assigning a sum of values to each option, each associated with the corresponding evaluation criterion, and weighted based on the relative importance of the corresponding criterion [23].

2.2b *MOORA (Multi-objective optimization on the basis of ratio analysis) (MOORA ratio system (MOORA RS) and MOORA reference point (MOORA RP))*: The MOORA approach is superior to other methods by taking into account and evaluating all objectives, taking into account all the interactions between alternatives and objectives at the same time. The method uses non-subjective and non-directional values instead of subjectively weighted normalization [24].

2.2c *VIKOR (VIsekriterijumsko KOmpromisno rangiranje)*: The VIKOR technique is a widely used method in selection and ranking problems and performance evaluations [25]. In this study, the weight of the strategy is 0.5 by consensus.

2.2d *COPRAS (complex proportional assessment)*: The COPRAS method is more straightforward than the other MCDM techniques, such as AHP, VIKOR and TOPSIS [26].

2.2e *TOPSIS (technique for order of preference by similarity to ideal solution) (TOPSIS Euclidean, TOPSIS Sity Cab, TOPSIS–Inf (Min)*: TOPSIS is a technique that allows the best choice among the alternatives using ideal measures. [27]. In this study, the threshold of indifference is 0.5.

2.2f *D'IDEAL (displaced ideal method)*: In D'IDEAL approach, the better system should have less distance from ideal [28].

2.2g *MABAC (Multi-attributive border approximation area comparison)*: The primary principle of the MABAC technique is that the evaluation is made according to the distance of the criteria functions of options to the boundary proximity area. In other words, a boundary proximity field is created. The criteria functions are then calculated for each alternative and their distance from the boundary proximity area is determined. Finally, by determining the criteria distances, the options are listed and the optimal alternative is selected [29].

2.2h *ORESTE (organisazion, RangEment ot SynTEze dedonnecs relationnelles)*: ORESTE is one of the ranking methods based on the relationship of being senior/important/ preferred. Although ORESTE method is not as widely used as the other outranking methods such as ELECTRE, PROMETHEE, etc., it has been used to solve a small number of decision problems [30].

In this study, the indifference coefficient is 0.05. The preference relation coefficient is 1.4. The coefficient of the decision-maker is 0.5. Lp (non-linear projection) is taken. Different Lp values are used in the analysis (Lp (*p* = 1 Average (Mean),=-1-Medium Harmonic, =2-Mean Square; and inf.))

2.2i *PROMETHEE (preference ranking organisation method for enrichment evaluations)*: PROMETHEE technique is a multi-criteria prioritization technique developed in 1982. The approach has been developed based on the difficulties of implementing prioritization techniques in the literature and has been used in some studies about supply management [30]. V shape, linear, Gauss and linear-Gauss functions were used instead of different normalization techniques in terms of preference functions.

2.2j *CODAS (combinative distance-based assessment)*: The preferability of alternatives to each other in the CODAS method is determined by Euclidean and Taxicab distances. The technique is based on an alternative's choice having a greater distance from the negative ideal solution. The first distance used for this purpose is the Euclidean distance. In cases where two options have equal Euclidean distance, the solution is obtained using Taksicab distance [31]. In this study, the threshold parameter is 0.02.

2.2k *GRA (grey relational analysis) (GRA and GRA (T))*: GRA is one of the standard techniques used in recent years as a guide in MCDM problems. Grey Relation Analysis is one of the subheadings of the Grey System Theory put forward in 1982 [32]. In this study, the grey relation degree is taken as 0.5.

2.2l *Entropy method*: The entropy technique is an objective method for determining the importance levels of the criteria without creating a hierarchical structure of the decision problem and calculating the criteria weights by taking into account the data without the subjective judgment of decision-makers such as AHP and Delphi techniques [33].

2.3 *Proposed method*

In this study, weights obtained by the entropy technique have been calculated by integrating the weights previously obtained in the literature. The formula is given below (Eq. 5). The flowchart of the proposed method is given in figure 1. Four different normalization methods and fifteen different MCDM techniques were used to develop a new hybrid methodology. All rankings were summed up and aggregate rankings were obtained.

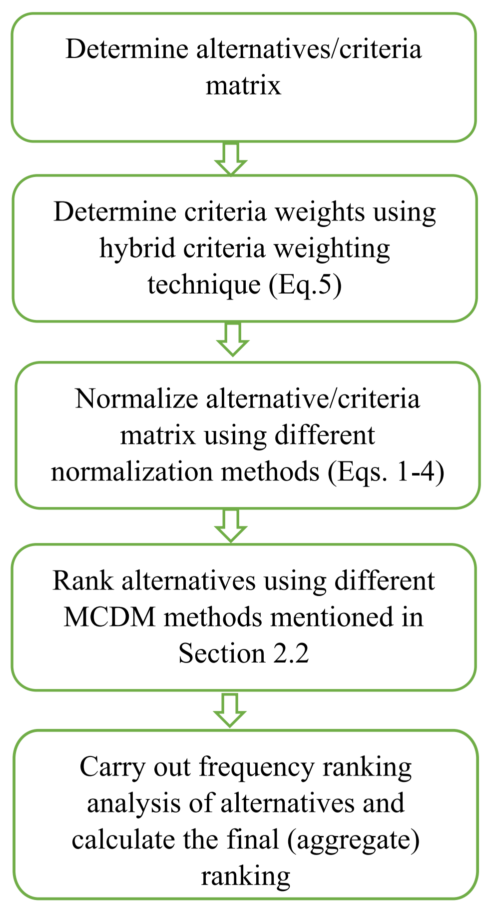

Figure 1. The flowchart of the proposed method.

Table 1. The decision matrix of Abhang and Hameedullah's study [13].

Alternative code	Lubrication-cooling condition	C1 Surface roughness (R_a(μm))	C2 Tool wear rate (T_w (mg/min))	C3 Cutting force (F_c (N))	C4 Chip-tool interface temperature (T_c (°C))
		Criteria			
A1	Dry	12.51	0.338	253.61	427
A2	Wet	10.97	0.336	221.6	390
A3	10% graphite+SAE-40	10.74	0.276	228	363
A4	10%MoS_2+SAE-40	10.68	0.274	230	351
A5	10%boric acid+SAE-40	10.48	0.249	155.2	320
A6	10%graphite+SAE-40	10.7	0.28	218	386
A7	15%MoS_2+SAE-40	10.53	0.276	228	365
A8	15%boric acid+SAE-40	10.45	0.247	256.96	326.88
A9	SAE-40	10.8	0.335	229	378

Table 2. The decision matrix of Rao's study [36].

Alternative code	Lubrication-cooling condition	C1 Processed surface roughness (R_{rms} (μm))	C2 Wear land (WL (mm/100))	C3 Feed force (F_f (N))	C4 Cutting force (F_c (N))
		Criteria			
A1	Dry	9	7	725	1324
A2	Water-soluble	7	16	485	1082
A3	Straight mineral oil	4.7	8	516	1098
A4	Chlorinated oil	4.9	15	494	1158
A5	Sulfo-chlorinated oil	8	6	393	962

Table 3. The decision matrix of Tiwari and Sharma's study [18].

Alternative code	Lubrication-cooling condition	C1 Nose wear (NW (mm))	C2 Flank wear (FW (mm))	C3 Feed force (F_f (N))	C4 Cutting force (F_C (N))	C5 Surface roughness (R_a(μm))
		Criteria				
A1	SCF-II (8%EP)	0.1505	0.1793	439.59	635.15	3.47
A2	SCF-II (12%EP)	0.1682	0.1881	423.8	627.39	3.93
A3	CCF-II (8%EP)	0.1316	0.1527	401.53	629.26	3.06
A4	CCF-II (12%EP)	0.1616	0.1962	495.04	668.12	3.75
A5	CMCF	0.2339	0.1949	544.86	663.26	4.75
A6	CSSCF	0.2094	0.2436	523.93	615.05	4.01
A7	Dry cutting	0.5357	0.54	271.14	503.15	3.3

SCF-II (8% of EP): sunflower-based cutting fluids with 8% of EP additive.

SCF-II (12% of EP): sunflower-based cutting fluids with 12% of EP additive.

CCF-II (8% of EP): canola-based cutting fluids with 8% of EP additive.

CCF-II (12% of EP): canola-based cutting fluids with 12% of EP additive.

CMCF: commercial mineral-based cutting fluid.

CSSCF: commercial semi-synthetic cutting fluid.

Table 4. Criteria weights used in the literature for three different case studies [13, 18, 36].

Case studies	Criteria weights of researchers
Case study-1 (C1/C2/C3/C4)	0.6938/0.1392/0.1225/0.0444
Case study-2 (C1/C2/C3/C4)	0.3/0.1/0.4/0.2
Case study-3 (C1/C2/C3/C4/C5)	0.2/0.2/0.2/0.2/0.2

Table 5. Criteria weights obtained by the hybrid weight (entropy weights + literature weight) for three different case studies.

Case studies	Criteria weights of hybrid weight methods
Case study-1 (C1/C2/C3/C4)	0.5476/0.2487/0.1894/0.0143
Case study-2 (C1/C2/C3/C4)	0.0385/0.0492/0.7612/0.1511
Case study-3 (C1/C2/C3/C4/C5)	0.0342/0.0131/0.0741/0.3918/0.4868

Table 6. Ranking results for the first case and literature studies.

Researches	Ranking
Literature study of Abhang and Hameedullah [13]	9-8-4-3-1-6-5-2-7
The present study with Abhang and Hameedullah's weights (aggregate ranking) [13]	9-8-4-3-1-6-5-2-7
The present study with hybrid weights (aggregate ranking)	9-8-4-3-1-6-5-2-7

$$w_{hybrid} = \frac{w_{literature} x w_{entropy}}{\sum_{i=1}^{n} \left(w_{literature} x w_{entropy} \right)} \quad (5)$$

i=1…n (the number of criteria)

Since each criterion has a different priority in multi-criteria decision-making, it is not assumed that all have equal weights, so finding the appropriate weight of importance for each criterion is one of the important task for multi-criteria decision-making. Various methods have been proposed in the literature for criterion weights and they can be divided into two groups. These are subjective and objective methods. Only the preferences of decision-makers are taken into account when determining the weights with subjective methods. Prejudice and bias can easily be mentioned using subjective methods. Objective methods determine the weights by using the available data without considering the preferences of the decision-maker. Using objective weights is more beneficial as it is difficult to obtain reliable subjective significance weights in many real-life problems [34]. Therefore, the entropy method, an objective weighting method, was integrated into subjective weightings in this study.

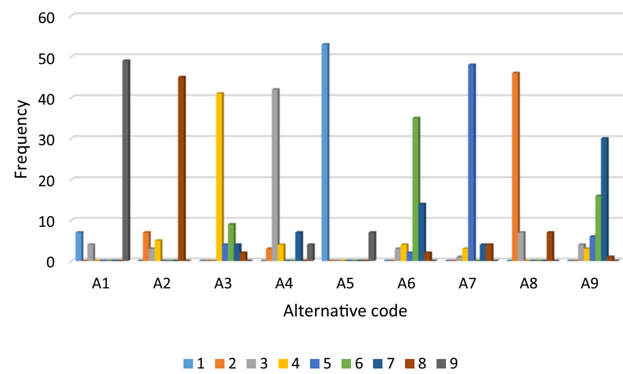

Figure 2. The frequency of rankings with literature weights (Case study 1).

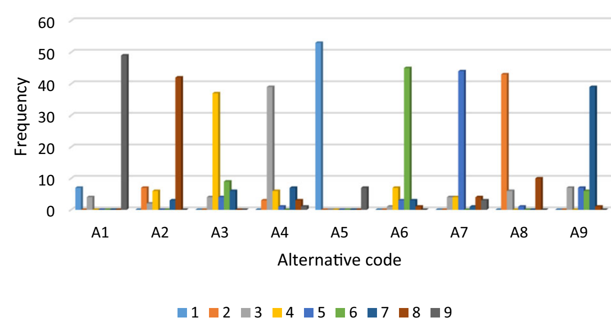

Figure 3. The frequency of rankings with hybrid weights (Case study 1).

Spearman correlation test was used to compare the results. It is a nonparametric measure of statistics and is used as a measure of dependence between two variables. Spearman's rank correlation coefficient (ρ) is a particular case of Pearson's product-moment correlation coefficient. To calculate ρ value, the sample data must be in the order of the two variables (Y and X). The Spearman correlation coefficient (ρ) is used instead of Pearson correlation to measure the linear relationship between two continuous variables when Pearson's assumptions are not met. Spearman correlation coefficient refers to the linear relationship between two ordinal variables or a sequential and continuous variable [35]. For these reasons, it is appropriate to use this test to compare the consistency of these rankings.

3. Case studies

3.1 *Case study 1*

Abhang and Hameedullah [13] used an MCDM method to select the optimum lubricant from many lubricants when turning EN-31 steel workpiece with CNMA120408

Table 7. Ranking results for second case and literature studies.

Researches	Rankings
1. Literature study of Rao (TOPSIS) [36]	3-5-2-4-1
2.Literature study of Rao (2007) (Graph Theory Matrix Approach (GTMA), WPM, AHP) [36]	5-4-2-3-1
3.Literature study of Rao (SAW) [36]	5-3-2-4-1
4.Literature study of Rao (Modified TOPSIS) [36]	4-5-2-3-1
5. The present study with Rao's weights (aggregate ranking) [36]	3-5-2-4-1
6.The present study with hybrid weights (aggregate ranking)	3-5-2-4-1

tungsten carbide inserts. In the experiments, a dry, wet and minimum amount of cutting fluid (SAE-40 mixed boric acid powder separately by graphite, MoS_2 and base oil) conditions were examined for the environmentally friendly production process. The decision matrix is presented in table 1.

3.2 *Case study 2*

Rao [36] provided experimental results for cylindrical turning to evaluate the most common, commercially available metal cutting fluids. Medium carbon steel was the workpiece material and an HSS cutting tool was used for the experiments. Four non-beneficial criteria were chosen. The quantitative evaluations of five cutting conditions are given in table 2.

3.3 *Case study 3*

Tiwari and Sharma [18] used different MCDM techniques to select the coolant used in the AISI304L turning process. Various vegetable-based cutting fluids containing the different and commercial fluids were determined in terms of five criteria and a decision matrix was established (table 3).

Table 4 shows the criteria weights (literature criteria weights) determined by different researchers for three different studies [13, 18, 36]. In the study, the calculations are

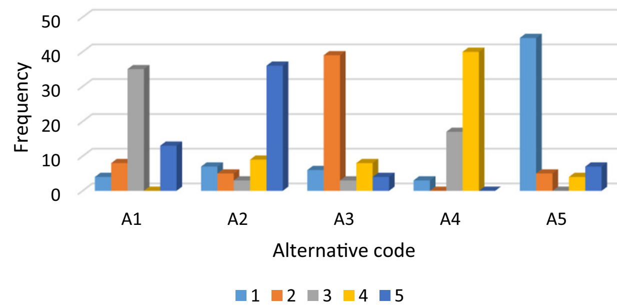

Figure 4. The frequency of rankings with literature weights (Case study 2).

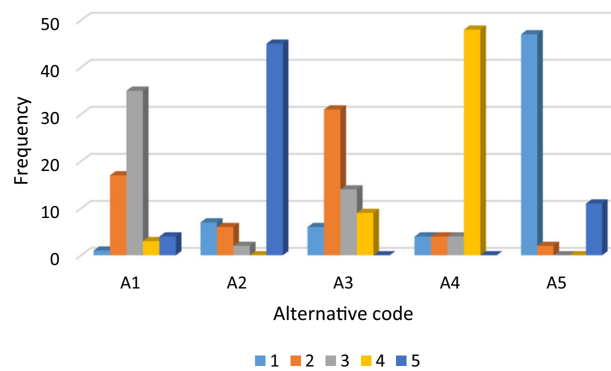

Figure 5. The frequency of rankings with hybrid weights (Case study 2).

Table 9. Ranking results for the third case and literature studies.

Researches	Rankings
1. Literature study of Tiwari and Sharma (2015) (SAW) [18]	2-3-1-4-7-6-5
2. Literature study of Tiwari and Sharma (2015) (WPM) [18]	2-3-1-4-6-5-7
3. The present study with Tiwari and Sharma (2015)'s weights (aggregate ranking) [18]	2-3-1-4-6-5-7
4. The present study with hybrid weights (aggregate ranking).	2-3-1-4-5-6-7

Table 8. Comparison of ranking results with Spearman correlation test.

Research no. according to Table 7		1	2	3	4	5-6
1	Correlation Coefficient	1	0.7	0.6	0.9	1
	Sig. (2-tailed)	.	0.18812	0.284757	0.037386	.
2	Correlation Coefficient	0.7	1	0.9	0.9	0.7
	Sig. (2-tailed)	0.18812	.	0.037386	0.037386	0.18812
3	Correlation Coefficient	0.6	0.9	1	0.7	0.6
	Sig. (2-tailed)	0.284757	0.037386	.	0.18812	0.284757
4	Correlation Coefficient	0.9	0.9	0.7	1	0.9
	Sig. (2-tailed)	0.037386	0.037386	0.18812	.	0.037386
5-6	Correlation Coefficient	1	0.7	0.6	0.9	1
	Sig. (2-tailed)	.	0.18812	0.284757	0.037386	.

Table 10. Comparison of ranking results with Spearman correlation test.

Research no. according to Table 9		1	2	3	4
1	Correlation Coefficient	1	0.892857	0.892857	0.857143
	Sig. (2-tailed)	.	0.006807	0.006807	0.013697
2	Correlation Coefficient	0.892857	1	1	0.964286
	Sig. (2-tailed)	0.006807	.	.	0.000454
3	Correlation Coefficient	0.892857	1	1	0.964286
	Sig. (2-tailed)	0.006807	.	.	0.000454
4	Correlation Coefficient	0.857143	0.964286	0.964286	1
	Sig. (2-tailed)	0.013697	0.000454	0.000454	.

carried out with the help of these criteria weights. Also, criteria weights obtained using the hybrid weighting method (literature criteria weights+entropy weights) are given using Eq. (5), (table 5). The calculations are performed with the help of these weights.

4. Results and discussion

The analysis was carried out with MATLAB software prepared by Mukhametzyanov [37].

4.1 *Case study 1*

Table 6 presents the ranking results for the first study. The results were compared with the literature study. It was seen that the same ranking result was obtained in comparison. The results of the study are consistent in this respect. The results show that 10% boric acid + SAE-40 base oil, 15% boric acid + SAE-40 base oil and 10% MoS_2 + SAE-40 are the best cutting conditions, while dry, wet and SAE-40 cutting conditions are the worst cutting conditions. Also, the frequency of rankings is given in figures 2 and 3. The figures have been obtained by analyzing all the rankings. With frequency analysis, all rankings were summed up and aggregate rankings were obtained. In figures, alternative-5 (A5) (10% boric acid + SAE-40 base oil) appears to be the best alternative in more than fifty calculations. The first condition (A1-dry cutting conditions) is the last alternative for nearly fifty calculations. Despite slight changes in frequency values, the rankings do not change. The same results were obtained in the literature [13].

4.2 *Case study 2*

Table 7 presents the ranking results for the second study. The calculated results were compared with the literature study. Besides, Spearman correlation test results are given in table 8. All the obtained rankings and literature rankings were tested. The results of the study are generally

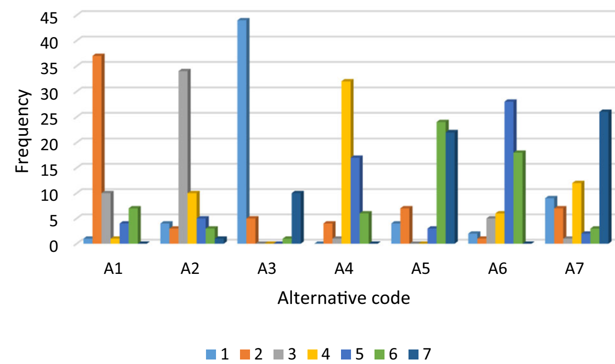

Figure 6. The frequency of rankings with literature weights (Case study 3).

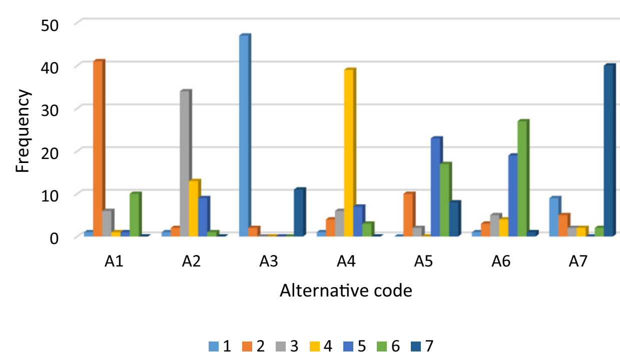

Figure 7. The frequency of rankings with hybrid weights (Case study3).

consistent with the Spearman correlation test at 5% significance level. When the study results are examined, it is seen that sulfo-chlorinated oil is the best alternative. The worst alternative is water-soluble conditions. Compared with the literature, the best alternative cluster is straight mineral oil, chlorinated oil and sulfo-chlorinated oil. The worst condition was found to be the water-soluble and dry cutting condition. In the literature, sulfo-chlorinated oil is a desired alternative [36]. In this context, it can be said that the results of the study are consistent with the literature studies. All the rankings were summed up in figures 4 and 5. Aggregate rankings were obtained and the frequency of rankings is given in the figures. The figures have been obtained by analyzing all the rankings. In figures, the fifth alternative (sulfo-chlorinated oil) is in the first place in nearly fifty calculations. The second alternative (water-soluble) takes the last place in nearly forty calculations. Despite slight changes in frequency values, the rankings do not change significantly.

4.3 *Case study 3*

Table 9 presents the ranking results for the third case study. The results were compared with the literature study. Spearman correlation test results were performed and all the literature rankings and obtained rankings were tested in table 10. The results of the study are consistent in this respect at the 5% level of significance. When the results of the study were examined, CCF-II (8% of EP) was found to be the best alternative, whereas CMCF was the worst alternative. In the literature, CCF-II (8% of EP) is the desired option [18]. When all studies are examined, CCF-II (8% of EP), SCF-II (8% of EP), SCF-II (12% of EP) are among the best alternatives, while CMCF, CSSCF and dry cutting conditions are the worst conditions. The frequency of rankings is given in figures 6 and 7. The figures have been obtained by analyzing all the rankings. With frequency analysis, all rankings were summed up and aggregate rankings were obtained. In figs., the third alternative (CCF-II (8% of EP)) takes first place in nearly forty-five calculations. The seventh alternative (dry cutting) takes the last place in nearly 25-45 calculations. Despite slight changes in frequency values, the rankings do not change significantly.

5. Conclusions

In this study, a new decision support system was proposed for the selection of cutting fluids. In this context, three different cutting fluid selection problems were taken from the literature. Fifteen different MCDM methods and four different normalization techniques were used to determine the optimum cutting conditions for these studies. In terms of weighting criteria, a new hybrid method was used in addition to the weights determined in the literature. The obtained rankings were compared with the Spearman correlation test. The results were consistent ($p<0.05$). The study help manufacturers and operators to make decisions in the selection of cutting fluids in the manufacturing environment. Different criteria weighting methods (Best-Worst, Level Based Weight Assesment, etc.) can be used in future studies. A detailed sensitivity analysis might be performed in terms of the obtained results.

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