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FUZZY AHP BASED DECISION SUPPORT SYSTEM FOR TECHNOLOGY SELECTION IN ABRASIVE WATER JET CUTTING PROCESSES

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Original scientific paper

Due to its remarkable abilities, the studies about abrasive water jet cutting process are rapidly increased in recent years. One of the main problems about this brilliant technology is to find the appropriate technology to use in cutting processes to increase surface quality. In this paper a fuzzy/crisp AHP based decision support system is proposed for the selection of appropriate technology for the cutting process of titanium. An application of the proposed models and their results are presented with comparisons. The results illustrated that both methods used in decision support pointed out the same technology with similar weights.

Keywords: *abrasive waterjet, fuzzy AHP, mutli-criteria decision making*

Sustav potpore neizrazitom AHP utemeljenom odlučivanju u izboru tehnologije u procesu rezanja abrazivnim vodenim mlazom

Izvorni znanstveni članak

Zbog svoje izvanredne mogućnosti, studije o procesu rezanja abrazivnim vodenim mlazom brzo su se povećale u posljednjih nekoliko godina. Jedan od glavnih problema u vezi s ovom briljantnom tehnologijom je pronaći odgovarajuće tehnologije za uporabu u procesima rezanja koja će povećati kvalitetu površine. U ovom radu predložen je sustav potpore neizrazitom/oštrom AHP utemeljenom odlučivanju u izboru odgovarajuće tehnologije za proces rezanja titana. Primjena predloženog modela i njegovi rezultati su prikazani s usporedbama. Rezultati su pokazali da obje metode koje se koriste za podršku odlučivanju ističu istu tehnologiju sa sličnim značajima.

Ključne riječi: *abrazivni vodeni mlaz, neizraziti AHP, višekriterijsko odlučivanje*

1 Introduction
Uvod

Abrasive Water Jet (AWJ); which may be accepted as a relatively new and nature-friendly technology for the industry, can simply be defined as the technological process that uses a transformation of the high-pressure jet to the high-speed waterjet as a tool for cutting substance, specially materials. As this technology has the ability of cutting some multicomponent materials in all directions, with simple shape cutting, multilayer materials cutting, shape heterogeneity and also the ability of usage on soft/ hard materials [1] without sparks caused during normal cutting processes with high accuracy and reliability, the studies about this brilliant technology rapidly increase in the last years [2, 3, 4, 5]. One important problem in the usage of AWJ cutting is to decide on the appropriate technology for the material to achieve the acceptable surface quality after the cutting process. Although the AWJ is a simple technology, the solution for this multi-criteria decision making (MCDM) problem is not simple as the waterjet cutting process includes many factors which directly or indirectly effect the cutting process and the surface quality. Generally the MCDM is used to solve problems that have several potential solution alternatives under several criteria or attributes that may be either tangible or intangible [6, 7]. They usually focus on human judgment/inference trying to implement it into the decision models [8]. One of the most preferred MCDM models in literature is the "Analytic Hierarch Process (AHP)" introduced by Saaty in 1970's [9, 10, 11]. The AHP, which can basically be defined as a theory of measurements which deals with quantifiable criteria that are based on the valuable experience and knowledge of decision makers that may be used as an input data for the designed MCDM model [12, 7]. Contrary to the nature of human decision making/judgment which contains and processes uncertainty or/and vagueness, crisp (discrete) sets only divide the given universe of discourse into two basic groups: members (which certainly belong to the set) and non-members (which certainly do not) which arises from their mutually exclusive structure that enforces the decision maker to set a clear-cut boundary between the decision variables and alternatives [13, 14, 15]]. From this point of view it can be easily proposed that this complex structure of MCDM best fits the applications of fuzzy logic and fuzzy set theory [16] which was introduced to the scientific world by Zadeh with the pioneer work of "Fuzzy Sets" in 1965 [17]. In this paper a decision support system (DSS) in fuzzy environment is developed for selecting the appropriate AWJ technology to have the best surface quality in terms of Ra (surface roughness profile parameter) for the cutting process of work piece surface of titanium. The methodology of AHP and fuzzy AHP (based on Chang's extent analysis) are both preferred and used as an evaluation tool [13]. This paper is organized as follows: in section 2, the preferred methods of the study, the AHP and fuzzy AHP models, are introduced; in section 3, the proposed DSS (based on AHP and fuzzy AHP) is introduced and details about the criteria determination process of the study are explained based on the empirical study of Hloch et al. [18]; in section 4, the application of the models and results are illustrated; finally in the last section, conclusions and further recommendations are highlighted.

2 AHP and fuzzy AHP models
AHP i neizraziti AHP modeli

2.1 AHP Model

The AHP, as emphasized before, is one of the most preferred and widely used MCDM tools [19]. It is basically a mathematical theory for deriving ratio scale priority vectors from positive reciprocal matrices with entries built up by paired comparisons [19, 20, 13]. It has the ability of enabling the decision maker to structure complex problems in a simple hierarchical form (see Fig. 1.) and give opportunity to evaluate a large number of quantitative and/or qualitative factors in a systematic way [21].

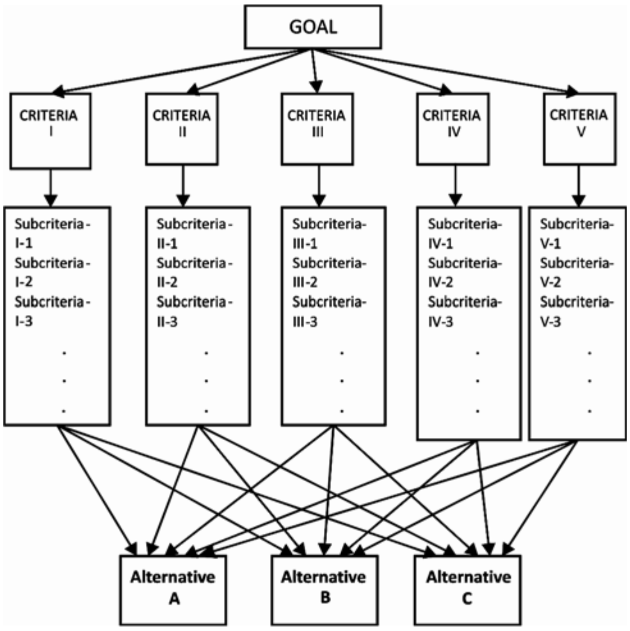

Figure1 *The hierarchical structure of AHP*
Slika 1. *Hijerarhijska struktura AHP*

Table 1 *An overview of classical methods of discarded munitions disposal (cakir)*
Tablica 1. *Pregled klasičnih metoda odlaganja odbačenog streljiva (cakir)*

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favour one activity over another
5	Strong Importance	Experience and judgment strongly favour one activity over another
7	Very Strong Importance	An activity is favoured very strongly over another; its dominance demonstrated in practice.
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.

After the hierarchical structure is constructed the prioritization procedure begins for determining the relative importance of the elements in each level using the scale in Tab. 1. The scale used in this process simply indicates dominance of each decision element over others with respect to the chosen property [10, 11, 25]. The basic steps of AHP can be summarized as follows [13, 22, 23, 24]:

- Problem definition including objectives and outcomes,
- Decomposition of the problem into a hierarchical structure (criteria, detailed criteria and alternatives),
- Composing the pair-wise matrices,
- Determination of weights for the decision elements using the eigen value method,
- Checking the consistency property of matrices,
- Obtaining an overall rating for the alternatives,
- Determination of the appropriate alternative with respect to overall rating.

For more details see [10, 11, 23, 25].

2.1 Fuzzy AHP Model
Neizraziti AHP model

Fuzzy set theory and fuzzy logic performed well under ambiguous or not well-defined conditions like decision making [19]. With the help of its capability of data processing using partial set membership functions this brilliant topic has the ability of donating intermediate values between the expressions mathematically which makes fuzzy logic a powerful device for impersonating the ambiguous and uncertain linguistic knowledge (Disaster). Fuzzy AHP which is based on the concept of fuzzy set theory uses these capabilities perfectly [17, 25]. This method rightfully occupies a remarkable place in literature of MCDM with so many applications to different fields of science and technology [13, 19, 24, 25]. In literature there also exist several fuzzy AHP approaches proposed by various authors which are all systematic approaches to the alternative selection via fuzzy set theory concept and hierarchical structure analysis. But in this study the Chang's extent FAHP is utilized with respect to its simplicity and wide usage [26]. In the following part of this section the Chang's extent analysis is briefly summarized [25, 26, 27]:

Let X be the object and G be the goal set as:

$$X = \{x_1, x_2, x_3, ..., x_n\}\ ,\ G = \{g_1, g_2, g_3, ..., g_n\}$$

respectively. As an extent analysis must be performed for each goal, respectively for each object $M_{gi}^{1},\ M_{gi}^{2}, ...\ M_{gi}^{m}$, i=1, 2,…, n, m extent analysis values can be obtained. Note that M_{gi}^{j} j=1, 2, .., m all are triangular fuzzy numbers (TFN) (Fig. 2).

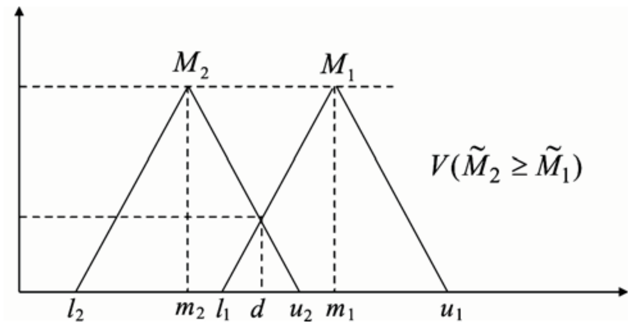

Figure 2 *The intersection between M_1 and M_2* [25]
Slika2. *Presjek između M_1 i M_2* [25]

The value of fuzzy synthetic extent with respect to the i^{th} object is defined as

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{1}$$

where

$$\left[\sum_{j=1}^{nm} \sum_{j=1} M_{gi}^{j} \right]^{-1}$$

is computed with equations (2) and (3) as follows.

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \quad (2)$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right). \quad (3)$$

The degree of possibility of

$M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ can be defined as:

$$V\left(\tilde{M}_2 \geq \tilde{M}_1\right) = \sup_{y \geq x} \left[\min\left(\mu_{\tilde{M}_1}(x), \mu_{\tilde{M}_2}(y) \right) \right] \quad (4)$$

where $\tilde{M}_1 = (l_1, m_1, u_1)$ and $\tilde{M}_2 = (l_2, m_2, u_2)$ are two triangular fuzzy numbers respectively.

Eq. (4) can be equivalently expressed as follows:

$$V\left(\tilde{M}_2 \geq \tilde{M}_1\right) = \text{htg}(\tilde{M}_1 \cap \tilde{M}_2) = \mu_{M_2}(d) =$$

$$= \begin{cases} 1, \text{ if } m_2 \geq m_1 \\ 0, \text{ if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, \text{ otherwise} \end{cases} \quad (5)$$

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i can be found as:

$$V(M \geq M_1, M_2, ..., M_k) = V\begin{bmatrix} (M \geq M_1) \text{ and } (M \geq M_2) \\ \text{and } (M \geq M_k) \end{bmatrix} = \quad (6)$$

$$= \min V(M \geq M_i), \text{ where } i = 1,2,3,...,k.$$

Assuming $d(A_i) = \min V(S_i \geq S_k)$ for $k = 1,2,....,n; k \neq i$ where A_i (i=1,2,...,n) are n elements, the weight vector can be given as

$$W' = (d'(A_1), d'(A_2), ..., d'(A_n))^T. \quad (7)$$

Finally the normalized weight vectors can be computed as

$$W = (d(A_1), d(A_2), ..., d(A_n))^T, \quad (8)$$

where weight W is nonfuzzy.

3 The proposed DSS and application
Predloženi DSS i primjena

AWJ cutting is used in many applications both in industrial and medical domain perfectly [1-20 other paper]. It has the ability of processing a wide range of materials without any time loss caused by a tool change [18]. But one of the main problems in that technology is to decide on the appropriate technology that is to be used in the process, which also is the main objective of this study. As stated before this study uses AHP and fuzzy AHP methods used to compose a DSS specially designed for having the best surface quality in terms of *Ra* in the cutting process of titanium. All criteria for the proposed DSS are determined made via questionnaire technique that is applied to specialists working with AWJ technology, profound discussions with experts and also utilizing the previous works in the literature about AWJ. Fig. 3 illustrates the body of the proposed model including criteria and alternatives. The outcome of questionnaire, discussions and previous works showed that the most preferred and suitable technologies in AWJ for titanium cutting process will be “Barton Garnet” and "Olivine" which also are determined as the alternatives to be chosen for DSS application. As the questionnaires designed for DSS include linguistic values, the fuzzy scale that is illustrated in Tab. 2 is used for fuzzification. For computing results and the model consistency a C# (CSHARP) based software is developed and used for the study.

***Table 2** The Fuzzy Scale*
***Tablica 2.** Eksperimentalni uvjeti*

Verbal Judgment	TFN	Reciprocal of TFN
Equal Importance	(1, 1, 2)	(1/2, 1,1)
Weak or slight	(1, 2, 3)	(1/3, 1/2, 1)
Moderate importance	(2, 3, 4)	(1/4, 1/3, 1/2)
Moderate plus	(3, 4, 5)	(1/5, 1/4, 1/3)
Strong importance	(4, 5, 6)	(1/6, 1/5, 1/4)
Strong plus	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strong or demonstrated importance	(6, 7, 8)	(1/8, 1/7, 1/6)
Very, very strong	(7, 8, 9)	(1/9, 1/8, 1/7)
Extreme importance	(8, 9, 9)	(1/9, 1/9, 1/8)

The pair-wise matrices and their weights for the crisp AHP (non-fuzzy) with regard to the main goal are illustrated in Tables 3-10.

***Table 3** Pairwise comparison matrix with respect to main goal*
***Tablica 3.** Matrica Pairwise usporedbe s obzirom na osnovni cilj*

	TS	AMFR	AT	DC	C	TP	
TS	1	2	2	2	3	4	
AMFR	½	1	2	2	3	3	
AT	1/2	1/2	1	1	2	1	
DC	1/2	1/2	1	1	7	9	
C	1/3	1/3	1/2	1	1	¼	
TP	1/4	1/3	1	1	4	1	
						Cr	0,0524

Calculations using input values illustrate that all input data is consistent with the consistency ratio of 0,0524. The following tables illustrate the input values gathered from questionnaires for each matrix.

***Table 4** Pairwise comparison matrix with respect to traverse speed (TS)*
***Tablica 4.** Matrica Pairwise usporedbe s obzirom na poprečnu brzinu (TS)*

TS	ALT-I	ALT-2	
ALT-1	1	5	
ALT-2	1/5	1	
		Cr	0

***Table 5** Pairwise comparison matrix with respect to abrasive mass flow rate (AMFR)*
***Tablica 5.** Matrica Pairwise usporedbe s obzirom na omjer abrazivnog masenog protoka (AMFR)*

AMFR	ALT-I	ALT-2	
ALT-1	1	3	
ALT-2	1/3	1	
		Cr	0

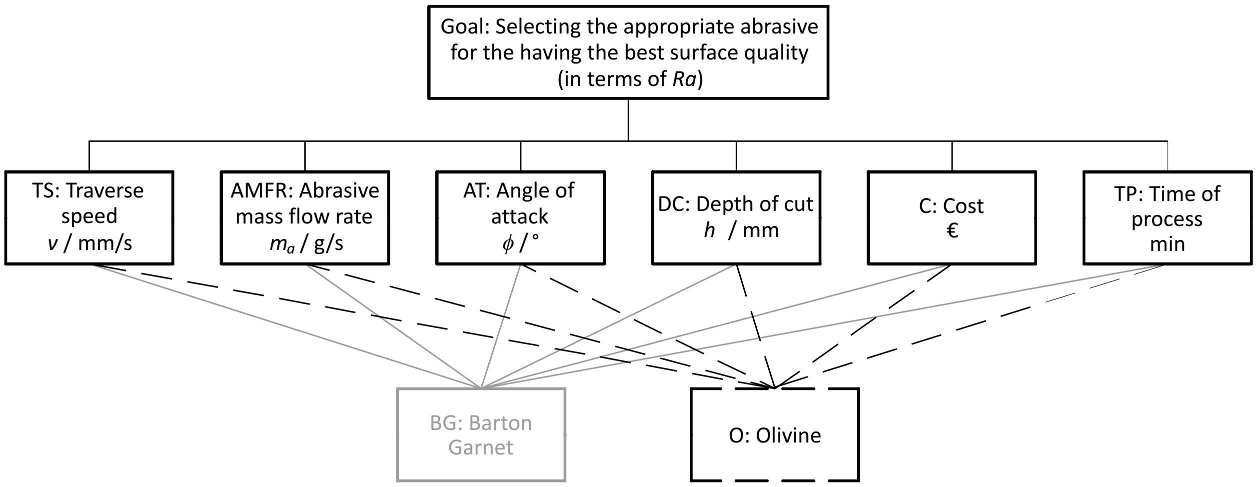

Figure 3 *Proposed model including criteria and alternatives*
Slika 3. *Predloženi model, uključujući kriterije i alternative*

Table 6 *Pairwise comparison matrix with respect to angle of attack (AT)*
Tablica 6. *Matrica Pairwise usporedbe s odnosu na napadni kut (AT)*

AT	ALT-I	ALT-2	
ALT-1	1	3	
ALT-2	1/3	1	
		Cr	0

Table 7 *Pairwise comparison matrix with respect to depth of cut (DC)*
Tablica 7. *Matrica Pairwise usporedbe sobzirom na dubinu rezanja (DC)*

DC	ALT-I	ALT-2	
ALT-1	1	7	
ALT-2	1/7	1	
		Cr	0

Table 8 *Pairwise comparison matrix with respect to cost (C)*
Tablica 8. *Matrica Pairwise usporedbe s obzirom na cijenu (C)*

C	ALT-I	ALT-2	
ALT-1	1	6	
ALT-2	1/6	1	
		Cr	0

Table 9 *Pairwise comparison matrix with respect to time of process (TP)*
Tablica 9. *Matrica Pairwise usporedbe s obzirom na vrijeme procesa (TP)*

TP	ALT-I	ALT-2	
ALT-1	1	3	
ALT-2	1/3	1	
		Cr	0

Weights of the crisp AHP (non-fuzzy) method final matrix illustrate that with respect to main goal and our criteria the best choice is "Barton Garnet" with a weight of 0,798.

Table 10 *Pairwise comparison matrix with respect to main goal*
Tablica 10. *Matrica Pairwise usporedbe s obzirom na osnovni cilj*

	Weights
Barton Garnet	**0,798**
Olivine	0,202
Sum	1

The results gathered from fuzzy AHP method also illustrated that "Barton Garnet" technology with a non-fuzzy weight of 0,867 is the best choice to use in AWJ technology to have the best surface quality in terms of *Ra* (surface roughness profile parameter) for the cutting process of work piece surface of titanium.

Table 11 *Pairwise comparison matrix with respect to main goal for fuzzy AHP*
Tablica 11. *Matrica Pairwise usporedbe s obzirom na glavni cilj neizrazitog AHP*

	Weights
Barton Garnet	**0,867**
Olivine	0,133
Sum	1

5 Conclusion and remarks
Zaključak i primjedbe

In the paper, a fuzzy/crisp (non-fuzzy) is proposed for the selecting the appropriate AWJ technology to have the best surface quality in terms of *Ra* for the cutting process of titanium. The weights for the criteria are determined by questionnaire technique that was applied to specialists working with AWJ technology, profound discussions with experts and also utilizing the previous works in the literature about AWJ. It is found out that there exist 5 important criteria and two appropriate alternatives for this process. The application results of both fuzzy and crisp model illustrated that "Barton Garnet" technology is the best choice with respect to the criteria of the proposed DSS to use in AWJ technology for having the best surface quality in terms of Ra for the cutting process of titanium. Further studies can be made using other widely used MCDM such as analytic network process or TOPSIS.

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