Mühendis ve Makina / Engineer and Machinery
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PLOUGHSHARES MATERIAL SELECTION: SHANNON'S ENTROPY BASED FUZZY TOPSIS APPLICATION

Ahmet Bilal ŞENGÜL[1*]

[1] Çanakkale Onsekiz Mart Üniversitesi, Mühendislik Fakültesi, Malzeme Bilimi ve Mühendisliği, Çanakkale

ORCID No : http://orcid.org/0000-0002-1939-0550

Keywords

Fuzzy TOPSIS, ploughshares material, material selection

Abstract

Material selection in the engineering design process is a challenging process because there are many materials and many contradictory features that must be together. The plough is the most important and basic tool of tillage. Large abrasions, cracks, and even sudden breaks can occur in the plough that cultivates the soil. For this reason, the material chosen to produce the ploughshares is extremely important. In this study, first of all, the criteria that are important in the selection of ploughshares iron were determined, and the criteria were weighted with the Interval Shannon Entropy method. Material preference ranking was made using "the Fuzzy Technique for Order Preference by Similarity to Ideal Solution" (FTOPSIS) technique. According to the study results, the order of the ploughshare's material selection criteria is, respectively, hardness, wear percentage, toughness, tensile stress, thermal conductivity, and cost. As a result of the selection made using the FTOPSIS method; It has been determined that 33MnCrB5(1.7185) should be preferred in the first place among the candidate materials, and then the order of preference should be 51CrV4(1.8159), 60SiMn5(SAE9262), 41CrMo4 (1.7225QT-4140), respectively. To measure the sensitivity of the results, sensitivity analysis was conducted at α=0.1, 0.5, and 0.9 levels.

* absengul@yahoo.com
doi : 10.46399/muhendismakina.1346068

PULLUK UÇ DEMİRİ MALZEME SEÇİMİ: SHANNON ENTROPİ TEMELLİ BULANIK TOPSIS UYGULAMASI

Anahtar kelimeler

Bulanık TOPSIS, pulluk ucu malzemesi, malzeme seçimi

Öz

Mühendislik tasarım sürecinde malzeme seçimi, çok sayıda malzeme olması ve birbirine zıt bir çok özelliğin bir arada olmasının gerekliliğinden zorlayıcı bir süreçtir. Pulluk, toprak işlemenin en önemli ve temel aracıdır. Toprağı işleyen pullukta büyük aşınmalar çatlaklar ve hatta ani kırılmalar oluşabilmektedir. Bu nedenle pulluk uç demiri üretimi için seçilen malzeme son derecede önemlidir. Bu çalışma da, öncelikle pulluk uç demiri seçiminde önemli olan kriterler belirlenmiş, kriterler Interval Shannon Entropi yöntemi ile ağırlıklandırılmıştır. Bulanık İdeal Çözüme Benzerliğe Göre Sıra Tercihi (FTOPSIS) tekniği kullanılarak malzeme tercih sıralaması yapılmıştır. Çalışma sonuçlarına göre, uç demiri malzeme seçim kriterleri sıralaması, sırasıyla; sertlik, aşınma dayanımı, tokluk, çeki gerilmesi, termal iletkenlik ve maliyet olarak tespit edilmiştir. FTOPSIS yöntemi kullanılarak yapılan seçim neticesinde; aday malzemelerden ilk sırada 33MnCrB5(1.7185)'nın tercih edilmesi gerektiği, ve daha sonrasında tercih sırasının, sırasıyla 51CrV4(1.8159), 60SiMn5(SAE9262), 41CrMo4 (1.7225QT-4140) olması gerektiği tespit edilmiştir. Sonuçların duyarlılığını ölçmek için, α=0.1,0.5 ve 0.9 düzeylerinde duyarlık analizi yapılmıştır.

Araştırma Makalesi			Research Article		
Başvuru Tarihi	:	19.08.2023	Submission Date	:	19.08.2023
Kabul Tarihi	:	22.01.2024	Accepted Date	:	22.01.2024

1. Introduction

Material plays an important role in engineering designs. When designing any product, it is necessary to select materials with specific properties that meet all current constraints and can guarantee optimum system performance (Sarfaraz Khabbaz, Dehghan Manshadi, Abedian, &Mahmudi, 2009). Material selection can be defined as the selection of the most suitable material among the materials to be used for the product while designing the product (Mamoon, Alhaji, & Abdullahi, 2021). It is not easy to choose materials suitable for product design. Ashby reported that there are over 160,000 materials of choice for engineers (Ashby, 2010). Materials can be selected, and many criteria affect the selection. Some of the criteria one may encounter in the material selection are hardness, high-temperature strength, low-temperature strength, stiffness, density, tensile strength, electrical conductivity, thermal conductivity, formability, weldability, cost, appearance, etc. (Hatamura, 1999). When the methods developed for material selection are examined, it is seen that they are grouped under two headings. The developed methods are elimination methods and selection methods. In the sieving methods, the unsuitable materials are eliminated step by step and the appropriate material is selected. Some of these methods are chart method (Ashby), survey method, and unit cost method. In the selection methods, the most suitable material is selected by listing the suitable materials under certain criteria (Balcı, 2004; Mamoon et al., 2021). The methods suitable for these methods are TOPSIS, MORPA, PROMETHEE, etc., which are under multi-criteria decision-making methods, are methods.

Some of the studies carried out by using the elimination and selection methods in material selection are as follows; Emovon and Oghenenyerovwho (2020), by scanning the literature for the period 1994-2019, examined 55 articles using Multi-Criteria Decision methods in material selection. As a result of the study, they stated that the cost criterion is the most frequently used criterion to decide on material selection and that MCDM methods offer a suitable methodology for solving material selection problems (Emovon and Oghenenyerovwho, 2020). Patnaik, Swain, Mishra, Puroit, & Biswas (2020) in their study, used MCDM methods for selecting the best alternative polymer composite material for engineering applications (Patnaik et al., 2020). Mamoon et al. (2021), compared the methods used in the literature to solve material selection problems and summarized the studies in the literature by classifying their methods as screening and ranking (Mamoon et al., 2021). Das and Sarkar (2021), developed a new multi-criteria decision-making model based on value constraints for the selection and ranking of materials. They tested the proposed method on four samples: material selection for the hip joint, fuel cell, high-temperature product, and a sailboat mast (Das and Sarkar, 2021). Chatterjee and Chakraborty (2021) used MCDM methods for the gear material selection problem (Chatterjee and Chakraborty, 2021). Zoghi, Rostami, Khoshand, & Motalleb (2022) used MCDM methods to design select materials that enable recyclability and reusability of building components (Zoghi et al., 2022). Aires and Ferreira (2022) proposed a new MCDM method for sustainable material selection problems (Aires and Ferreira, 2022). Ordu and Der (2023) used MCDM methods to evaluate suitable polymeric materials for the fabrication of flexible vibrating heat pipes (Ordu and Der, 2023). Zakeri, Chatterjee, Konstantas, & Ecer (2023) proposed a new decision making method called Simple Ranking Process (SRP) to solve the material selection problem and stated that it is a suitable methodology for solving challenging MCDM problems (Zakeri et al., 2023). Remadi and Frikha (2023) used MCDM methods for green material selection under uncertainty (Remadi and Frikha, 2023). Martínez-Gómez and Eduardo (2023) used multi-criteria selection procedures for the selection of an alternative composite material for the high voltage circuit of gasoline internal combustion engines (Martínez-Gómez and Eduardo, 2023). Gaalice and Abdelrhman (2024) used the FAHP-FTOPSIS technique to select appropriate bearing ring materials for pharmaceutical applications. They compared 5 candidate materials under thirteen criteria (Gaalice and Abdelrhman, 2024). Raju, Palli, Prasad, Menda, & Ramakrishna (2024) used MCDM for the selection of natural fiber composites instead of synthetic fiber composites used as materials in the fields of aviation, transportation, architecture, and sports. They compared 7 composite materials under the criteria of density, hardness, tensile strength, and toughness, as well as water absorption and specific heat capacity (Raju et al., 2024).

When the literature review is examined, it is seen that MCDM methods are widely used in material selection problems. In this study, the material selection was made for the ploughshares. The plough is the most important and basic tool of tillage. Large abrasions, cracks (Gürsel and Köftecioğlu, 2006), and even sudden breaks can occur in the plough that cultivates the soil. For this reason, the material chosen for plough production is extremely important. The ploughshares are the plough element that takes the first abrasive effect and impacts the plough. Some of the studies on the selection of ploughshares material are as follows.

Bayhan (1996), in his study, investigated the wear behavior of soil tillage tools. He found significant correlations between the amount of wear and hardness in the ploughshares and established regression models for them. In addition, it has been determined that the carbon and manganese content of the material affects the wear behavior (Bayhan, 1996). Er (2003) investigated the wear behavior by coating boron on ploughshares made of six different materials (Er, 2003). Çakır (2019) investigated the wear behavior of four different materials by applying various heat treatment and surface treatments to be used in the production of ploughshares iron (Çakır, 2019). Kalácska, De Baets, Fauconnier, Schramm, Frerichs, & Sukumaran (2020) performed wear experiments on the wear of cultivator tines made of 27MnB5 steel to investigate the change in mass, size, hardness, and microstructure. They developed a model by conducting field studies (Kalácska et al., 2020). Singh, Chatha, & Sidhu (2020) used hard facing to increase the wear percentage of the ploughshare. They determined that the wear percentage is effective in the hardness of the material, as well as in its microstructure and chemical composition (Singh et al., 2020). Singh, Chatha, & Sidhu (2021), ploughshares material; They investigated the wear behavior by coating two different Fe-based claddings on the base material made of EN-42 steel to be tested at two different soil moisture levels (Singh et al., 2021). Boydaş (2023) investigated the effect of different ploughshares geometries on the pulling force of the machine in defining the soil-machine relationship using computer simulation (Boydaş, 2023).

As can be seen from the literature review, many types of materials are used, and different surface treatments are applied in the production of the ploughshares. Determining the right material and surface treatment is an exceedingly difficult decision problem. It is of significant importance to know which criteria should be considered and the relative importance of the criteria while choosing the ploughshares material. In the literature, there is no study on which criteria should be considered in the material selection for the ploughshares. In addition, there was no study using MCDM methods in the selection of ploughshares material. In this study, first, the criteria that are important in the selection of the ploughshare's material were determined by considering the expert opinion and the literature, and the order of importance of the criteria was determined by the Interval Shannon Entropy method. Then, 33MnCrB5(1.7185), 60SiMn5(SAE9262), 51CrV4(1.8159), 41CrMo4 (1.7225QT-4140) steels, which can be used as ploughshares material, were taken as material alternatives and a preference order was made. Since expert opinion was taken while evaluating the criteria and most of the alternatives contain interval data, fuzzy numbers were used to solve the problem. "The Fuzzy Technique for Order Preference by Similarity to Ideal Solution" (FTOPSIS) technique was used to determine the order of preference of ploughshares materials. Sensitivity analyses were performed at α =0.1,0.5 and 0.9 levels.

Determining the correct material and surface treatment is a difficult decision problem. No study has been found that evaluates more than one material together in terms of multiple material properties and mechanical behaviors. In the study, it was investigated which criterion was how important among the criteria, taking into account the cost criteria, as well as other criteria, in the selection of plow tip material. In addition, evaluating many materials at the same time and selecting the most suitable plow tip material is the contribution of this study to the literature. Multi-criteria decision-making methods have been successfully applied to material selection problems in the literature. To measure the sensitivity of the results obtained, calculations were made at three alpha cut-off levels, α = 0.1, 0.5, and 0.9.

In the next parts of the study, the criteria, and alternatives for the selection of ploughshares material are defined, then the steps of the methods used for material selection are explained and the analysis results are discussed, and the conclusion part is concluded.

2. Determınation of Criteria and Alternatives For Materıal Selection of The Ploughshares

Tillage is the process of physically improving the soil to make it suitable for growing plants (Singh et al., 2020). Parts that contact the soil during processing are subject to strong abrasive wear (Kalácska et al., 2020). Wear tillage tools is a very important problem for farmers all over the world. At this point, the end iron comes to the forefront as the element that meets these effects in the first degree. The ploughshares, which are subject to severe wear, are also at risk of breakage. If the ploughshares are short life, it will waste precious time in the crop season, as well as the cost of replacing the ploughshares. To extend the service life of the ploughshares as much as possible, the factors affecting the ploughshare's damage should be taken into account in the selection of the ploughshare's material. It takes place in a wide range such as "These factors are material properties (hardness, toughness, and microstructure), soil type (particle hardness, size, angularity, and compaction) with also the operational (velocity, working depth) and environmental (moisture, temperature) conditions" (Kalácska et al., 2020). Within the scope of the study, the criteria given in Table 1 were determined for the selection of ploughshares material based on the literature studies and the expert opinion of the plough-producing company. The solution was made by accepting the variables as constant except for the criteria discussed.

Table 1. Ploughshares material selection criteria

Criteria		Definition
C_1	Hardness (HB)	"Hardness is the ability to withstand surface indentation (localized plastic deformation) and scratching"[1]
C_2	Toughness (Notch impact strength) (J)	"Toughness is the ability of a material to absorb energy and plastically deform without fracturing"[2]
C_3	Wear percentage (loss at %)	"Wear is mechanically induced surface damage that results in the progressive removal of material due to relative motion between that surface and a contacting substance or substances"[3]

C_4	Tensile strength (Mpa)	"Strength of a material is its ability to withstand this applied load without failure or plastic deformation"[4]
C_5	Thermal conductivity (W/m-K)	"The heat transfer characteristics of a solid material are measured by a property called the thermal conductivity"[5]
C_6	Cost of material ($/tonne)	Material cost

1 https://material-properties.org/what-is-hardness-of-low-alloy-steel-41xx-steel-chromoly-steel-definition/

2 https://material-properties.org/what-is-toughness-definition/

3 https://material-properties.org/what-is-wear-types-classification-and-differences-definition/

4 https://material-properties.org/strength-of-materials-tensile-yield/

5 https://www.thermal-engineering.org/what-is-thermal-conductivity-definition/

Higher hardness, higher toughness, higher tensile stress, higher abrasion resistance (Singh et al., 2020), and higher thermal conductivity (in order not to increase the local temperature excessively in harsh conditions), are important criteria that the ploughshares are exposed to.

Ploughshares are exposed to impact loads that can reach extremely high values from time to time, as well as abrasion during operation. Although extremely hard materials show high resistance to abrasion, they may not be sufficiently resistant to impacts. While high-hardness material is needed against abrasion, high toughness is required against impacts (Gürsel and Köftecioğlu, 2006). This inverse relationship between the hardness and impact strength of the ploughshares complicates the selection of the ploughshares material. 1991 date DIN 11100 standard leaves the choice of material to the manufacturer (Gürsel and Köftecioğlu, 2006).

To meet the forces and keep the shear stress and wear as small as possible, the ploughshares are manufactured from a special material (Gürsel and Köftecioğlu, 2006). Hardness, toughness, abrasion resistance, tensile stress, etc. of the material. features are strongly related to each other. In this study, four strong candidate materials, which are widely used, were selected from a wide material universe that can be used in soil cultivation. The chemical properties of four selected candidate steels are given in Table 2.

In Table 3, the mechanical properties and cost per ton values of 33MnCrB5(1.7185), 60SiMn5(SAE9262), 51CrV4(1.8159), 41CrMo4 (1.7225QT-4140) steels, which were taken into consideration as the selection criteria, are given as candidate ma-

Table 2. Chemical contents of candidate ploughshares steel (%)

Material	Carbon (C)	Chromium, (Cr)	Manganese, Mn	Phosphorus, P	Silicon, Si	Sulfur, S	Others
33MnCrB5 (1.7185)[1]	0.3-0.36	0.3-0.6	1.2-1.5	≤0.025	≤0.4	≤0.035	Bor (B) 0.0008-0.005
60SiMn5 (SAE9262)[2]	≤0.55-0.65	0.25-0.4	≤0.75-1	≤0.04	≤1.8-2.2	≤0.04	-
51CrV4 (1.8159)[3]	0.47-0.5	0.90-1.2	0.7-1.1	max 0.025	max 0.40	Max 0.025	Vanadyum (V) 0.1-0.25
41CrMo4 (1.7225QT-4140)[4]	0.38-0.43	0.8-1.1	0.75-1.0	≤0.035	0.15-0.30	≤0.040	Molybdenum, (Mo), 0.15-0.25 Iron,(Fe), 96.785-97.77

1 33MnCrB5-2, 1.7185, 27MnCrB5-2, 1.7182 – boron steel (virgamet.com)
2 SAE 9262 steel plate, SAE 9262 sheet, SAE 9262 coil - Carbon steel - (steelss.com)
3 33MnCrB5-2, 1.7185, 27MnCrB5-2, 1.7182 – boron steel (virgamet.com)
4 AISI 4140 Steel, oil quenched, 25 mm (1 in.) round [845°C (1550°F) quench, 540°C (1000°F) temper] (matweb.com)

Table 3. Decision matrix of the ploughshare's materials in terms of criteria

	Hardness (HB)	Toughness (J)	Abrasion percentage (loss in %)	Tensile strength (Mpa)	Thermal conductivity (W/m-K)	Material cost ($/tonne)
33MnCrB5 (1.7185)	450-560[1]	50[1]	0.969[2]	1050-1300[3]	40-45[4]	580[5]
60SiMn5 (SAE9262)	300-400[6]	26[7]	0.883[2]	1158[7]	32.3-44.2[8]	850[9]
51CrV4 (1.8159)	360-490[10]	30[11]	0.985[2]	1200-1800[10]	40-45[12]	800[13]
41CrMo4 (1.7225QT-4140)	311[14]	42[2]	0.905[2]	1075[14]	33-42.6[14]	800-900[15]

1 "33MnCrB5-2, 1.7185, 27MnCrB5-2, 1.7182 – boron steel (virgamet.com)"
2 (Acar, 2019)
3 33MnCrB5-2 / 1.7185 - SteelNumber - Chemical composition, equivalent, properties
4 Ovako 33MnCrB5-2 (EN10083-3:2006) Steel (matweb.com)
5 Sup9 60si2mn 51crv4 28mnb5 33mncrb5 Yassı Çubuklar Levha Çelik -
6 60 SiMn5 Çelik Özellikleri, 10.908 Çelik Özellikleri | Uslular (uslularhadde.com)
7 SAE 9262 steel plate, SAE 9262 sheet, SAE 9262 coil - Carbon steel - (steelss.com)
8 SAE 9262 Steel, Datasheet, Properties, Cross-Reference Table, Suppliers (steel-grades.com)
9 60simn5 Bahar Çelik Alaşımlı Çelik Soğuk Haddelenmiş Çelik - Buy Strip Steel Steel Coil Steel Sheet Spring Steel Alloy Steel,60simn5,High Carbon Steel Tool Steel Cold Rolled Alloy Steel Product on Alibaba.com
10 51CrV4 1.8159 Alloy Spring Steel Strip (fushunsteel.com)
11 Material (basedosteel.com)
12 Ovako 51CrV4 SB9292 Steel, Tempering (matweb.com)
13 https://www.alibaba.com/product-detail/42CrMo4-EN-1-7225-42CrMo-Hot_1600753090106.html?spm=a2700.galleryofferlist.p_offer.d_title.46c97006mFenQ0&s=p
14 AISI 4140 Steel, oil quenched, 25 mm (1 in.) round [845°C (1550°F) quench, 540°C (1000°F) temper] (matweb.com)
15 42CrMo4/4140/1.7225 – qilusteelstock.com (qilu-steelstock.com)

terials for the manufacture of ploughshares. This table also generates the values of the decision matrix for the FTOPSIS method.

3. Methodology

Decision-making is the determination of the option or options that can give the most appropriate result by evaluating all aspects of one or a series of problems that need to be finalized at each management level (Toksarı and Toksarı, 2011). It is a difficult problem to solve because it requires the evaluation of more than one alternative under more than one criterion. In decision problems, it is important to assign and weight the criteria correctly. In criterion weighting, the relative importance of the criteria is determined by matching the criteria with a value. In a decision problem, the weight vector $w=[w_1, w_2,\ldots,w_n]$

$$w_1 + w_2 + \cdots + w_n = 1, \qquad w_j \geq 0\,, \qquad (j = 1,2,\ldots,n) \tag{1}$$

shows as (Roszkowska, 2013). On the other hand, since linguistic expressions are generally used in the evaluation of criteria and alternatives, its solution becomes difficult. Many real-life problems involve imprecise data, which are sometimes inaccurate, sometimes intermittent, and sometimes fuzzy data (Lotfi and Fallahnejad, 2010). The differences in perception in the way people think, their subjective behaviors, and uncertainties in their goals can be explained by the concept of blur. Fuzzy logic is a type of logic used when the membership degrees of the object classes encountered in real life cannot be fully defined and the binary logic system is insufficient to explain these thoughts (Zadeh, 1965). A fuzzy set is characterized by a membership function, with each element denoted by membership degrees from 0 to 1. The sign denoting blur is indicated by the symbol "~"(Yalçın Seçme and Özdemir, 2010). In a fuzzy set, the fuzzy set is expressed as follows to show the first element member and the second element membership degree (Zimmermann, 2001),

$$\tilde{A} = \mu_{\tilde{A}}(x_1)/x_1 + \mu_{\tilde{A}}(x_2)/x_2 + \cdots + \mu_{\tilde{A}}(x_i)/x_i \tag{2}$$

Fuzzy sets are defined by membership functions, so there are as many types of fuzzy numbers as there are membership functions. (Baykal and Beyan, 2004). In this study, the triangular membership function was used. Generally, the triangular fuzzy number $\tilde{A}$ is the number with the starting point l, the ending point u, and the vertex m and is shown as $[l, m, u]$ (Zadeh, 1965);

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \leq x \leq m \\ \dfrac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \text{ or } x < l \end{cases} \tag{3}$$

The fuzzy number values given in Table 4 were considered to determine the criterion weights.

Table 4. Linguistic expressions and triangle fuzzy number value (Ayağ & Özdemir, 2006)

Intensity of Importance	Fuzzy number	Definition	Triangular fuzzy scale	Fuzzy number	Triangular fuzzy scale
1	$\tilde{1}$	Equally important/preferred	(1,1,2)	$\tilde{1}^{-1}$	$(\frac{1}{2},\frac{1}{1},\frac{1}{1})$
3	$\tilde{3}$	Moderately more important/preferred	(2,3,4)	$\tilde{3}^{-1}$	$(\frac{1}{4},\frac{1}{3},\frac{1}{2})$
5	$\tilde{5}$	Strongly more important/preferred	(4,5,6)	$\tilde{5}^{-1}$	$(\frac{1}{6},\frac{1}{5},\frac{1}{4})$
7	$\tilde{7}$	Very strongly more important/preferred	(6,7,8)	$\tilde{7}^{-1}$	$(\frac{1}{8},\frac{1}{7},\frac{1}{6})$
9	$\tilde{9}$	Extremely more important/preferred	(8,9,10)	$\tilde{9}^{-1}$	$(\frac{1}{10},\frac{1}{9},\frac{1}{8})$

Interval Shannon's entropy based on a-level sets was used to determine the criterion weights. Shannon's entropy method was developed by Lotfi and Fallahnejad (2010) and allowed to perform operations by converting triangular fuzzy numbers to interval data. The solution algorithm of Shannon's fuzzy entropy based on α-level sets is given below (Lotfi and Fallahnejad, 2010).

3.1 Interval Shannon Entropy Method

Step 1: The pairwise comparison matrix $(\widetilde{D})$ of the criteria consisting of triangular fuzzy numbers is transformed into the matrix A with the interval given, using equations 5 and 6 according to the α cut levels (usually taken as α =0.1;0.5;0.9).

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{12} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{4}$$

$$(\tilde{x}_{ij})_{\alpha}^{L} = l + \alpha * (m - l), (\tilde{x}_{ij})_{\alpha}^{R} = u + \alpha * (m - u) \tag{5}$$

$$\left[(\tilde{x}_{ij})_{\alpha}^{L}, (\tilde{x}_{ij})_{\alpha}^{R}\right] = \left[\min_{x_{ij}} \left\{x_{ij} \in R \middle| \mu_{\tilde{x}_{ij}}(x_{ij}) \geq \alpha\right\}, \max_{x_{ij}} \left\{x_{ij} \in R \middle| \mu_{\tilde{x}_{ij}}(x_{ij}) \geq \alpha\right\}\right] \quad 0 \leq \alpha \leq 1 \tag{6}$$

$$A = \begin{bmatrix} [x_{11}^L, x_{11}^R] & [x_{12}^L, x_{12}^R] & \dots & [x_{1n}^L, x_{1n}^R] \\ [x_{21}^L, x_{21}^R] & [x_{22}^L, x_{22}^R] & \dots & [x_{2n}^L, x_{2n}^R] \\ \vdots & \vdots & \ddots & \vdots \\ [x_{m1}^L, x_{m1}^R] & [x_{m2}^L, x_{m2}^R] & \dots & [x_{mn}^L, x_{mn}^R] \end{bmatrix} \tag{7}$$

Step 2: The obtained values are normalized with equations 8 and 9.

$$p_{ij}^L = \frac{x_{ij}^L}{\sum_{j=1}^m x_{ij}^R} \qquad i = 1,2,\dots,m \quad and \quad j = 1,2,\dots,n \tag{8}$$

$$p_{ij}^R = \frac{x_{ij}^R}{\sum_{j=1}^m x_{ij}^R} \qquad i = 1,2,\dots,m \quad and \quad j = 1,2,\dots,n \tag{9}$$

Step 3: The entropy values of the lower and upper bound range are calculated with equations 10 and 11.

$$e_i^L = min\left\{-e_0 \sum_{i=1}^m p_{ij}^L lnp_{ij}^L, - e_0 \sum_{i=1}^m p_{ij}^R lnp_{ij}^R,\right\} j = 1,2,\dots,n \tag{10}$$

$$e_i^R = max\left\{-e_0 \sum_{i=1}^m p_{ij}^L lnp_{ij}^L, - e_0 \sum_{i=1}^m p_{ij}^R lnp_{ij}^R,\right\} j = 1,2,\dots,n \tag{11}$$

In these equations,

$e_0 = (lnm)^{-1}$, and $p_{ij}^L lnp_{ij}^L$ or $p_{ij}^R lnp_{ij}^R$ is defined as 0 if $p_{ij}^L = 0$ or $p_{ij}^R = 0$.

Step 4: Set the lower and the upper bound of the interval of diversification is calculated by equations 12 and 13.

$$d_i^L = 1 - e_i^R \qquad j = 1,2,\dots,n \tag{12}$$

$$d_i^R = 1 - e_i^L \qquad j = 1,2,\dots,n \tag{13}$$

Step 5: The lower bound and upper bound of interval weight is calculated by equations 14 and 15. The result is obtained by taking the arithmetic average of these values.

$$w_i^L = \frac{d_i^L}{\sum_{s=1}^{n} d_s^L} \qquad j = 1,2,\dots,n \tag{14}$$

$$w_i^R = \frac{d_i^R}{\sum_{s=1}^{n} d_s^R} \qquad j = 1,2,\dots,n \tag{15}$$

After the criteria were weighed, the FTOPSIS method was used to weight the alternatives. The steps of this method are given below,

3.2. The FTOPSIS method

TOPSIS is one of the most commonly used methods in multi-objective decision problems (Wang and Elhag, 2006). FTOPSIS steps can be followed as (Rathod and Kanzaria, 2011; Chen-Tung Chen, 2000);

Step 1: First, criterion weights $(\widetilde{w}_j)$ are determined (determined by the Interval Shannon's Entropy method).

Step 2: The decision matrix $\tilde{C}$, which consists of all alternatives and criteria, is expressed as:

$$\tilde{C} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{12} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{array} \tag{16}$$

$$W = \left[\widetilde{w}_1, \dots, \widetilde{w}_j, \dots, \widetilde{w}_n,\right] \tag{17}$$

Here, A_i,i=1,2,…,m shows the alternatives to be selected and C_j,j=1,2,…,n shows the criteria. Triangle fuzzy numbers are denoted as $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $\widetilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$

Step 3: The fuzzy decision matrix $\tilde{C}$, is normalized. The normalized decision matrix is denoted by $\tilde{R}$ and is expressed as:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{mxn} \tag{18}$$

Elements B and C, are benefit and cost criteria,

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{c_j^*}, \frac{m_{ij}}{c_j^*}, \frac{u_{ij}}{c_j^*}\right), \quad j \in B; \tag{19}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{u_{ij}}, \frac{a_j^-}{m_{ij}}, \frac{a_j^-}{l_{ij}}\right), \quad j \in C; \tag{20}$$

$$j \in B \quad ise \quad c_j^* = \max_i u_{ij} \tag{21}$$

$$j \in C \quad ise \quad a_j^- = \min_i a_{ij} \tag{22}$$

Step 4: Equations 23 and 24 are used to construct the weighted normalized fuzzy decision matrix.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn}, \quad i = 1,2,\dots,m, \quad j = 1,2,\dots,n \tag{23}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \tag{24}$$

Step 5: "Determine positive ideal (V^+) and negative ideal solutions (V^-). The fuzzy ideal (best) and fuzzy negative ideal (worst) solutions can be expressed as":

$$V^+ = \left\{\left(\sum_i^{max} \tilde{v}_{ij}/j \in J\right), \left(\sum_i^{min} \tilde{v}_{ij}/j \in J'\right)/i = 1,2,\dots,m\right\} = \{\tilde{v}_1^+, \tilde{v}_2^+, \tilde{v}_3^+, \dots, \tilde{v}_n^+\} \tag{25}$$

$$V^- = \left\{\left(\sum_i^{min} \tilde{v}_{ij}/j \in J\right), \left(\sum_i^{max} \tilde{v}_{ij}/j \in J'\right)/i = 1,2,\dots,m\right\} = \{\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^-, \dots, \tilde{v}_n^-\} \tag{26}$$

Step 6: "Calculate separation measures. The separation (distance) of each alternative from V^+ and V^- can be currently calculated as"

$$s_i^+ = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^+\right) \qquad i = 1,2,\dots m \tag{27}$$

$$s_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \qquad i = 1,2,\dots m \tag{28}$$

Step 7: "Calculate the relative closeness to the ideal solution as described before",

$$R_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad i = 1,2,\dots m \tag{29}$$

Step 8: Rank reference order. Choose an alternative with maximum R_i or rank alternatives according to R_i in descending order.

4. Results and Discussion

In the study, four candidate materials, which were determined to be used in the production of ploughshares, were selected under six criteria. To determine the criterion weights, the opinions of 6 expert engineers, each with ten to thirty years of design and manufacturing experience, were taken in a large enterprise class agricultural machinery manufacturing enterprise operating in the agricultural machinery manufacturing sector. In Table 5, the pairwise comparison matrix of the expert opinions on the criteria is given.

Table 5. Pairwise comparison matrix of end iron material selection criteria according to expert opinions

	C_1	**C_2**	**C_3**	**...**	**C_6**
C_1	[1.000,1.000,1.000]	[1.333, 1.667, 2.667]	[0.122, 0.141, 0.167]	...	[3.333, 4.333, 5.333]
C_2	[0.417,0.778,0.833]	[1.000, 1.000, 1.000]	[1.431,1.781,2.139]	...	[5.333, 6.333, 7.333]
C_3	[6.667,7.667,8.667]	[3.389, 4.067, 4.750]	[1.000,1.000,1.000]	...	[5.333, 6.333, 7.333]
C_4	[0.256,0.437,0.792]	[0.256, 0.437, 0.458]	[0.122,0.141,0.167]	...	[3.417, 4.111, 4.833]
C_5	[0.778,1.133,1.500]	[1.084, 1.400, 1.750]	[0.306,0.511,0.538]	...	[4.000, 5.000, 6.000]
C_6	[0.195,0.244,0.333]	[0.139, 0.162, 0.195]	[0.139,0.162,0.195]	...	[1.000,1.000,1.000]

The data in Table 5 was converted to interval data using equations 5 and 6. Then, using equations 7, 8, 9, 10, 11, 12, and 13, the values in Table 6 were obtained for α =0.1, α =0.5 and α =0.9 levels.

Table 6. The values $[e_i^L, e_i^R]$, $[d_i^L, d_i^R]$

	α =0.1		α =0.5		α =0.9	
	$[e_i^L, e_i^R]$	$[d_i^L, d_i^R]$	$[e_i^L, e_i^R]$	$[d_i^L, d_i^R]$	$[e_i^L, e_i^R]$	$[d_i^L, d_i^R]$
C_1	[0.544, 0.643]	[0.357, 0.456]	[0.579, 0,632]	[0.368, 0.421]	[0.609, 0.619]	[0.381, 0.391]
C_2	[0.692, 0.798]	[0.202, 0.308]	[0.744, 0.801]	[0.199, 0.256]	[0.791, 0.802]	[0.198, 0.209]
C_3	[0.692, 0.798]	[0.244, 0.314]	[0.723, 0.758]	[0.242, 0.277]	[0.753, 0.759]	[0.241, 0.247]
C_4	[0.782, 0.881]	[0.119, 0.218]	[0.827, 0.881]	[0.119, 0.173]	[0.870, 0.881]	[0.119, 0.130]
C_5	[0.759, 0.889]	[0.111, 0.241]	[0.820, 0.891]	[0.109, 0.180]	[0.880, 0.894]	[0.106, 0.120]
C_6	[0.820, 0.941]	[0.059, 0.180]	[0.877, 0.942]	[0.058, 0.123]	[0.931, 0.944]	[0.056, 0.069]

By using Equations 14 and 15, interval values were found, and criteria weights were determined for all three alpha levels by taking the arithmetic average. The results are given in Table 7.

Table 7. The interval and crisp weight of the criteria

	α =0.1		α =0.5		α =0.9	
	$[w_i^L, w_i^R]$	w_i	$[w_i^L, w_i^R]$	w_i	$[w_i^L, w_i^R]$	w_i
Hardness (HB)	[0.327, 0.266]	0.296 [1]	[0.336, 0.294]	0.315 [1]	[0.346, 0.336]	0,341 [1]
Toughness (J)	[0.185, 0.179]	0.182 [3]	[0.182, 0.179]	0.181 [3]	[0.180, 0.179]	0,179 [3]
Wear percentage (loss at %)	[0.223, 0.183]	0.203 [2]	[0.221, 0.194]	0.208 [2]	[0.219, 0.212]	0,215 [2]
Tensile strength (Mpa)	[0.109, 0.127]	0.118 [5]	[0.109, 0.121]	0.115 [4]	[0.108, 0.111]	0,110 [4]
Thermal conductivity (W/m-K)	[0.102, 0.141]	0.121 [4]	[0.099, 0.126]	0.112 [5]	[0.096, 0.103]	0,100 [5]
Material cost($/tonne)	[0.054, 0.105]	0.079 [6]	[0.053, 0.086]	0.069 [6]	[0.051, 0.059]	0,055 [6]

Bracket [.] denotes the ranking order.

When Table 7 was evaluated, the ranking of the ploughshares material selection criteria was similar for all alpha levels. Accordingly, the first-degree important criterion in the selection of ploughshares material is the hardness of the material. Following this, in order of importance, wear percentage, toughness, tensile stress, thermal conductivity, and material cost took place. It is known that the wear percentage of the ploughshares is primarily dependent on the hardness of the ploughshare's material. As the hardness increases in the martensite region, the wear shows a linear decrease (Gürsel and Köftecioğlu, 2006). The important thing in terms of ploughshares production is to choose an economically priced material that can achieve as high a wear percentage as possible without breaking. There is a strong relationship between Hardness Toughness, Abrasion percentage, and tensile strength. As can be seen in Table 7, material hardness has emerged as the first-degree important criterion. This is an expected result. Abrasion percentage is the second most important criterion. Abrasion damage in tillage is perhaps the most exposed damage mechanism. However, while this is achieved, it is necessary not to fracture the material. In this context, it is a reasonable result to take place the toughness criterion following the abrasion percentage. Subsequently, tensile stress, thermal conductivity, and material cost take place. Tensile strength is an important selection criterion that interacts with the previous three criteria. Although thermal conductivity is important in terms of ensuring that the local heat generated because of friction is removed from the material and cooled, it is seen that it is less important than the other four criteria. Finally, the cost of materials takes place, which shows that there is not much difference between material prices and that functionality is important before cost.

After the criterion weights were determined, the FTOPSIS method was used to select the most suitable material among the options for the ploughshares. Interval values in Table 3 were converted into triangular fuzzy numbers and included in the analysis. The middle value of the triangular fuzzy number was obtained by taking the arithmetic average of the upper and lower values of the interval values. The decision matrix values used for the FTOPSIS analysis are given in Table 8.

Table 8. Ploughshares selection criteria and decision matrix for materials

	Hardness	**Toughness**	**Wear percentage**	**Tensile strength**	**Thermal Cond.**	**Mat. Cost**
33MnCrB5	[450, 505, 560]	[501, 501, 501]	[0.969, 0.969, 0.969]	[1050, 1175, 1300]	[40, 42.5, 45]	[580, 580, 580]
60SiMn5	[300, 350, 400]	[26, 26, 26]	[0.883, 0.883, 0.883]	[1158, 1158, 1158	[32.3, 38.25,44.2]	[850, 850, 850]
51CrV4	[360, 425, 490]	[30, 30, 30]	[0.985, 0.985, 0.985]	[1200, 1500, 1800]	[40, 42.5, 45]	[800, 800, 800]
41CrMo4	[311, 311, 311]	[42, 42, 42]	[0.905, 0.905, 0.905]	[1075, 1075, 1075]	[33, 37.8, 42.6]	[800, 850, 900]

The values in Table 9 were obtained by using the equations 19,20,21,22,23,24,25 and 26 in the FTOPSIS steps. While the criteria are included in the solution; hardness, toughness, tensile strength, and thermal conductivity were evaluated as the highest best, and the wear percentage and material cost were evaluated as the lowest best.

Table 9. The comparison results for ploughshares materials

	α=0.1				α =0.5				α =0.9			
	s_i^+	s_i^-	R_i	Rank	s_i^+	s_i^-	R_i	Rank	s_i^+	s_i^-	R_i	Rank
33MnCrB5	0,066	1,141	0,945	1	0,061	1,147	0,950	1	0,053	1,155	0,956	1
60SiMn5	0,323	0,118	0,267	3	0,325	0,115	0,261	3	0,329	0,110	0,251	3
51CrV4	0,224	0,218	0,494	2	0,223	0,217	0,493	2	0,224	0,216	0,490	2
41CrMo4	0,340	0,122	0,264	4	0,344	0,118	0,255	4	0,349	0,111	0,242	4

At α =0.1, α =0.5, and α =0.9 levels, the material order for the ploughshares was the same. The order of preference of candidate materials to be used in the ploughshares was determined as 33MnCrB5(1.7185), 51CrV4(1.8159), 60SiMn5(SAE9262), 41CrMo4 (1.7225QT-4140), respectively. Among these materials, 33MnCrB5 is the type of material that is widely preferred in soil cultivation with its high manganese content and alternatives such as 27MnCrB5, 30MnCrB5, and 38MnCrB5, 33MnCrB5 steel stands out in soil cultivation with its high hardness and toughness value and low cost per ton. 51CrV4 steel, which draws attention with its vanadium content, is used as spring steel and is a preferred spring steel in soil cultivation. With its high manganese and silicon content, 60SiMn5 steel is widely used in the manufacture of machine parts such as springs, circlips, and bolts, and is also used in the field of soil cultivation equipment. 41CrMo4 is a material that gives a good surface appearance with its high chromium content, finds a wide application area in the machinery manufacturing sector, and responds well to heat treatment with high availability. Although it is not common, it also finds use in soil cultivation.

5. Conclusion

The selection of ploughshares material, which is exposed to abrasion and working under impact loads in soil cultivation, was made using MCDM methods. First, criteria were determined according to the literature and expert opinion. Then, the data obtained from the expert opinion were converted into fuzzy numbers and the order of importance of the criteria was determined with the Interval Shannons' Entropy method. According to this, the order of the ploughshare's material selection criteria, respectively; hardness, wear percentage, toughness, tensile strength, thermal conductivity, and material cost. 33MnCrB5(1.7185), 60SiMn5(SAE9262), 51CrV4(1.8159), 41CrMo4 (1.7225QT-4140) steels are considered as ploughshares material options. Analysis was performed with the FTOPSIS method. It has been determined that 33MnCrB5(1.7185) should be preferred as the ploughshare's material first, and then 51CrV4(1.8159), 60SiMn5(SAE9262), 41CrMo4 (1.7225QT-4140) should be preferred, respectively. In future studies, a similar methodology can be used for material selection.

In the study, the material selection problem was created to select the plow tip iron. Multi-Criteria Decision Making Methods are successfully applied in material selection problems in the literature, so the most appropriate material selection was made using this method for plow tip iron selection. Since there is no study in the literature on plow tip material selection using the Fuzzy MCDM method, this study attempted to contribute to the literature. One of the limitations of this study is that not all the criteria and alternatives required for material selection can be obtained. Additionally, material selection with the MCDM method can be used as an introductory study in terms of investment planning.

As a result of the sensitivity analysis, the material selection order was the same. In future studies, studies can be conducted by consulting experts in different fields, using different criteria and materials, and using different FMCDM methods. In addition, in experimental studies, studies can be carried out starting from MCDM methods to determine which feature is more important in finding the most suitable material in material selection.

References

Aires, R. F. and Ferreira, L. (2022). "A New multi-criteria approach for sustainable material selection problem". *Sustainability,* 14(18), 11191, http://dx.doi.org/10.3390/su141811191

Ashby, M. F. (2010). Materials selection in mechanical design. Woburn, UK:Butterworth Heinemann.

Ayağ, Z. and Özdemir, R. G. (2006). "A fuzzy AHP approach to evaluating machine tool alternatives". *Journal of Intelligent Manufacturing,* 17(2), 179–190. https://doi.org/10.1007/s10845-005-6635-1

Balcı, A. (2004). *Basınçlı Kaplarda Malzeme Seçimi için Karar Destek Sistemi Geliştirilmesi.* (Yüksek Lisans Tezi). Gazi Üniversitesi, Fen Bilimleri Enstitüsü, Ankara.

Bayhan, Y. (1996). *Trakya bölgesinde imal edilen bazı toprak işleme aletlerinin uç demirlerindeki aşınma ve aşınmaya etki eden bazı etkenlerin saptanması üzerine bir araştırma.* (Doktora Tezi). Trakya Üniversitesi, Fen Bilimleri Enstitüsü, Edirne.

Baykal, N. ve Beyan, T. (2004). Bulanık mantık ilke ve temelleri. Ankara, Türkiye: Bıçaklar Kitapevi.

Boydaş, M. (2023). "Farklı ağız yapısına sahip kültivatör uç demirlerinin çeki kuvveti üzerine etkisinin sonlu elemanlar yöntemi kullanılarak belirlenmesi". *Tekirdağ Ziraat Fakültesi Dergisi,* 20(2), 306–317. https://doi.org/10.33462/jotaf.1087131

Chatterjee, S. and Chakraborty, S. (2021). "Material selection of a mechanical component based on criteria relationship evaluation and MCDM approach". *Materials Today: Proceedings,* 44, 1621–1626. https://doi.org/10.1016/j.matpr.2020.11.817

Chen-Tung Chen. (2000). "A note on Extension of fuzzy TOPSIS method based on interval-valued fuzzy sets". *Fuzzy Sets and Systems,* 114, 1–9. https://www.sciencedirect.com/science/article/abs/pii/S0165011497003771

Çakır, F. G. (2019). *Pulluk uç demirlerine uygulanan yüzey işlemlerinin aşınma davranışına etkilerinin incelenmesi* (Yüksek Lisans Tezi). Manis Celal Bayar Üniversitesi, Fen Bilimleri Enstitüsü, Manisa.

Das, M. C. and Sarkar, B. (2021). "Fusion between full consistency method and ideal solutions with constraint on values for material selection: A Consilient conspectus approach". *Journal of The Institution of Engineers (India)*: Series

C, 102(5), 1211–1230. https://doi.org/10.1007/s40032-021-00739-y

Emovon, I. and Oghenenyerovwho, O. S. (2020). "Application of MCDM method in material selection for optimal design: A review". *Results in Materials, 7* (June), 100115. https://doi.org/10.1016/j.rinma.2020.100115

Er, Ü. (2003). *Bor Yayınımıyla Yüzeyi Sertleştirilmiş Çeliklerin Aşınmaya Karşı Dayanımlarının ve Pulluk Uç Demirlerinde Uygulama Olanaklarının Araştırılması.* Doktora tezi. Eskişehir Osmangazi Üniversitesi, Fen Bilimleri Enstitüsü, Eskişehir.

Gaalice, N. and Abdelrhman, A.M. (2024). "A Fuzzy logic approach for selecting bearing ring materials in pharmaceutical applications". *Results in Materials*, 21, 100513. https://doi.org/10.1016/j.rinma.2023.100513

Gürsel, K. T. and Köftecioğlu, E. Y. (2006). "Structural analysis of elements of two-bottom mouldboard plough". *Journal of Engineering and Natural Sciences, Sigma,* 0232, 46–55. https://www.ytusigmadergisi.com/pdfs/229.pdf

Hatamura, Y. (1999). The Practice of Machine Design. London: UK: Clarendon Press.

Kalácska, Á., De Baets, P., Fauconnier, D., Schramm, F., Frerichs, L. and Sukumaran, J. (2020). "Abrasive wear behaviour of 27MnB5 steel used in agricultural tines". *Wear,* 442–443. https://doi.org/10.1016/j.wear.2019.203107

Lotfi, F. H. and Fallahnejad, R. (2010). "Imprecise shannon's entropy and multi attribute decision making". *Entropy,* 12(1), 53–62. https://doi.org/10.3390/e12010053

Mamoon, A., Alhaji, A. U. and Abdullahi, I. (2021). "Application of neural network for material selection: A Review". *International Journal of Material Science and Engineering,* 7(2), 1–6. https://doi.org/10.14445/23948884/ijmse-v7i2p101

Martínez-Gómez, J. and Eduardo, P. J. (2023). "Coil high voltage spark plug boots insulators material selection using MCDM, simulation, and experimental validation". *Processes,* 11(1291), 2–23. https://doi.org/10.3390/pr11041292

Ordu, M. and Der, O. (2023). "Polymeric Materials selection for flexible pulsating heat pipe manufacturing using a comparative hybrid MCDM approach", *Polymers,* 15(13), 1–20. https://doi.org/10.3390/polym15132933

Patnaik, P. K., Swain, P. T. R., Mishra, S. K., Purohit, A. and Biswas, S. (2020)." Composite material selection for structural applications based on AHP-MOORA approach". *Materials Today: Proceedings,* 33, 5659–5663. https://doi.org/10.1016/j.matpr.2020.04.063

Raju, S., Palli, S., Prasad, P. D., Menda, V. R. and Ramakrishna, B. (2024). "A hybrid AHP-TOPSIS, MOORA technique for multi-objective optimization of thermal, mechanical, and water absorption behavior of epoxy/hemp, pine apple, and palm fiber composites". *Journal of the Chinese Institute of Engineers,* 47(1), 23-36. https://doi.org/10.1080/02533839.2023.2274092

Rathod, M. K. and Kanzaria, H. V. (2011). "A methodological concept for phase change material selection based on multiple criteria decision analysis with and without fuzzy environment". *Materials and Design,* 32(6), 3578–3585. https://doi.org/10.1016/j.matdes.2011.02.040

Remadi, F. D. and Frikha, H. M. (2023). "The triangular intuitionistic fuzzy numbers CODAS method for solving green material selection problem". *International Journal of Operational Research,* 46 (3), 398–415. https://doi.org/10.1504/IJOR.2023.129409

Roszkowska, E. (2013). "Rank ordering criteria weighting methods – A Comparative overview", *Optimum. Studia Ekonomiczne,* 5 (65), 14–33. https://doi.org/10.15290/ose.2013.05.65.02

Sarfaraz Khabbaz, R., Dehghan Manshadi, B., Abedian, A. and Mahmudi, R. (2009). "A simplified fuzzy logic approach for materials selection in mechanical engineering design". *Materials and Design,* 30(3), 687–697. https://doi.org/10.1016/j.matdes.2008.05.026

Yalçın Seçme, N and Özdemir, A. İ. (2010). "Bulanık analitik hiyerarşi yöntemi ile çok kriterli stratejik tedarikçi seçimi: Türkiye örneği". *Atatürk Universitesi İktisadi ve İdari Bilimler Fakültesi Dergisi,* 22(2), 175–190.

Singh, J., Chatha, S. S. and Sidhu, B. S. (2020). "Effect of surface alloying on wear behaviour of EN-47 steel". *Materials Today: Proceedings,* 21,1340–1349. https://doi.org/10.1016/j.matpr.2020.01.172

Singh, J., Chatha, S. S. and Sidhu, B. S. (2021). "Abrasive wear characteristics and microstructure of Fe-based overlaid ploughshares in different field conditions". *Soil and Tillage Research,* 205(August 2020). https://doi.org/10.1016/j.still.2020.104771

Toksarı, M. and Toksarı, D. M. (2011). "Bulanık Analitik Hiyerarşi Prosese (AHP) yaklaşımı kullanılarak hedef pazarın belirlenmesi". *ODTÜ Gelişme Dergisi,* 38 (Nisan), 51–70.

Wang, Y. M. and Elhag, T. M. S. (2006). "Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment". *Expert Systems with Applications,* 31(2), 309–319. https://doi.org/10.1016/j.eswa.2005.09.040

Zadeh, L. A. (1965). "Fuzzy sets". *Information and Control,* 8, 338–353.

Zakeri, S., Chatterjee, P., Konstantas, D. and Ecer, F. (2023). "A decision analysis model for material selection using simple ranking process". *In Scientific Reports* 13 (1). Nature Publishing Group UK. https://doi.org/10.1038/s41598-023-35405-z

Zimmermann, H. J. (2001). "Fuzzy set theory and its applications". In Fuzzy Set Theory-and Its Applications (4th Edition). *Springer Science+Business Media,* LLC. https://doi.org/10.1007/978-94-010-0646-0

Zoghi, M., Rostami, G., Khoshand, A and Motalleb, F. (2022). "Material selection in design for deconstruction using Kano model, fuzzy-AHP and TOPSIS methodology". *Waste Management and Research,* 40(4), 410–419. https://doi.org/10.1177/0734242X211013904