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A NOVEL HYBRID DECISION-MAKING MODEL: FUZZY AHP-TOPSIS APPROACH FOR PRIORITISING COPPER SMELTING PROCESSES

NOV HIBRIDNI MODEL ZA ODLOČITEV PREDNOSTNEGA POSTOPKA PRETALJEVANJA BAKRA NA OSNOVI PRISTOPA Z NAVIDEZNO LOGIKO AHP-TOPSIS

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The construction of a copper smelting facility and its undisturbed and profitable business undoubtedly contribute to the development of each country's economy. These facilities employ many workers and produce a large amount of copper, reducing imports and dependence on this important raw material, thereby improving the economic situation in a given country. More than a hundred copper smelters operate worldwide, many of which use different types of copper extraction processes. Strict legislation relating to ecology and environmental protection as well as stakeholder involvement in selecting and constructing copper smelting facilities limit the maximisation of short-term economic objectives. The prioritisation of technological processes for the extraction of copper must consider the impacts of often mutually opposing economic, technical and environmental objectives. No research from the available literature analyses the economic, technical and environmental parameters systematically. Studies have mainly dealt with exploring individual influences of factors through the use of one selection method. This paper presents the development of a novel hybrid AHP-TOPSIS model in fuzzy environments that will provide both informative decisions and optimum results of decision making.

Keywords: hybrid model, AHP, TOPSIS, fuzzy environment, copper smelting processes

Konstrukcija ter nato uspešna izdelava in uporaba naprav za pretaljevanje bakra je nedvomno donosen posel, ki v celoti prispeva k razvoju ekonomije vsake države. Te naprave zaposljujejo veliko ljudi in proizvajajo velike količine strateške kovine kot je baker, zmanjšujejo uvoz in odvisnost od pomembnih osnovnih surovin ter tako izboljšujejo ekonomske razmere v dani državi. Več kot sto talilnic bakra deluje po svetu in pri tem uporabljajo različne postopke ekstrakcije bakra. Strožja ekološka in okoljska zakonodaja, kakor tudi vključevanje delničarjev v izbiro vrste naprave za pretaljevanje bakra omejuje in skrajšuje roke za ekonomske odločitve. Dajanje prednosti tehnološkim procesom ekstrakcije bakra je pogosto v nasprotju z ekonomskimi, tehniškimi in okoljskimi zahtevami, ko se ocenjuje realizacija projekta. Avtorji tega članka v literaturi niso našli ustrezne analize, ki bi sistematično istočasno upoštevala ekonomske, tehniške in okoljske parametre. Obstoječe študije se v glavnem ukvarjajo z raziskovanjem posameznih vplivov z uporabo ene izbrane metode. V tem članku avtorji predstavljajo razvoj novega hibridnega modela AHP-TOPSIS v navideznem okolju, ki naj bi pripomogel tako do odločilnih informacij za optimalne rezultate odločanja v tako imenovanem »decision making« postopku.

Ključne besede: hibridni model, analitično hierarhični proces (AHP), tehnika prednostne ureditve za idealno rešitev (TOPSIS), zamegljeno oziroma navidezno okolje, proces pretaljevanja bakra

1 INTRODUCTION

Without a doubt copper represents one of the key products needed for the economic development of any country. Copper extraction dates back to prehistoric times, to be more precise, to the Copper Age or Chalcolithic Age.[1] Although it is one of the oldest exploited metals, its significance has not diminished. On the contrary, the significance of this metal is greater than ever, and its positive growth trend continues. However, the increase in the copper production has a negative impact on the environment. This has led to a constant development of new technological solutions for reducing the adverse effects of copper extraction.[2–4] In the last half century, there was progress in technological processes for extracting non-ferrous metals, especially copper. Thus, production capacities were increased, and the quality was improved. However, the negative environmental impact remained.[5,6]

The manufacturing sector plays a significant role in fostering sustainable economic growth in many developed economies. The study by Behun et al.[7] showed that changes in the manufacturing and sales sectors are almost immediately reflected in the gross domestic product (GDP) changes. In a survey conducted by Vishal Chandr Jaunky (2013), the influence of copper consumption on the economic development of 16 countries was analysed.[8] Based on this research and other relevant studies from the literature, it can be concluded that copper consumption and production are crucial elements of a country's long-term economic development.[9–13] The fact is that copper smelting facilities employ many workers

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and produce a significant amount of copper, contributing to a better economic situation in each country. The construction of such industrial facilities contributes to reducing the import of this extremely important raw material and improving the living standards in the environment where a copper facility operates. Therefore, it is essential to develop an adequate model for selecting the optimal copper smelting process, taking into account the importance of these facilities for the local economy and the economy of the country.

The modern environment is full of challenges and, in such conditions, decision-makers often need quick and efficient tools that help them quickly model and optimise several alternative solutions, and then compare them based on different prerequisites or performance criteria.[14–16] This problem can be solved by using the multi-criteria decision making methodology (MCDM), which provides a wide range of mathematical models that can give effective solutions.

In this paper, eight of the most effective and frequently used technological processes for the pyrometallurgical extraction of copper were selected after consulting experts. In a study conducted by Kapusta in 2004, over 50 active copper smelters worldwide were analysed based on economic, ecological and technological factors. The study provides an insight into the frequency of a specific type of technological process used for extracting copper.[17–21]

Based on a broad literature review, it has been concluded that no research systematically analyses the economic, environmental and technical parameters for prioritising copper smelting processes. There is mainly available research on analysing separate effects of various factors.[3,22,23] Therefore, the essence of this study was to determine which current technological process achieves the optimal pre-set economic goals while complying with technological and environmental standards. In addition to filling the literature gap, applying this systematic decision model would increase the cleaner “red metal” production with technological efficiency and economic justification. This approach determines the optimal technological process for the given situation.

The hybrid AHP-TOPSIS method in a fuzzy environment was used to rank the analysed technological processes for copper extraction according to the 11 mentioned parameters. The ranking was based on 11 economic, technological and environmental parameters selected based on previous consultations with the experts in the copper production field. The importance of the chosen parameters for copper processing can be found in the papers by Davenport et al.,[24] Moskalyk & Alfantazi,[17] Kapusta,[18] Schlesinger et al.,[19] Najdenov et al.,[25] and others. These parameters represent the criteria for the model proposed in this paper. The scientific contribution of this paper is reflected in the integration of the economic aspect with technological and environmental parameters.

2 OVERVIEW OF THE CONSIDERED TECHNOLOGICAL PROCESSES AND PARAMETERS

Extracting copper from copper ores can be achieved through pyrometallurgy and hydrometallurgy. The literature review shows that hydrometallurgical processes are more environmentally friendly than pyrometallurgical ones, but most copper smelting facilities use pyrometallurgical processes.[21] Pyrometallurgical processes occur at high temperatures, leading to very rapid reactions. Thus, by applying a pyrometallurgical process, copper is obtained much faster than with the hydrometallurgical process. In this way, producing a larger amount of copper within a much shorter period is possible. It also has a significant economic impact that reflects on a greater reversal of assets and the ability to make a profit in a shorter time.[26–28] For the reasons mentioned above, the research focused only on pyrometallurgical processes. When selecting a specific technological process for extracting copper, in addition to the technological, two other basic criteria were considered: economic and environmental acceptability. The environmental acceptability of the technology was significantly actualised at the end of the twentieth century. As the economic parameter is the most influential when choosing the technology, and it is prominent in pyrometallurgical procedures, about 80 % of copper produced today is extracted primarily through pyrometallurgical processes.[19,21] In addition, numerous improvements that occurred in the previous period led not only to an increase in the production infrastructure and capacity but also in a reduction of the negative impact on the environment.[29–32]

The parameters selected as the criteria in this paper significantly impact the implementation of the technological process, its economic viability and the environment.

Copper ores contain a relatively small percentage of copper. Therefore, copper ores must be enriched by flotation before further processing in smelting facilities to achieve optimal conditions for a copper production. The product of copper flotation operation is copper concentrate.[24] The amount of concentrate that will be processed should be taken into account when choosing the appropriate technological process. An economical copper production can be achieved if larger quantities of concentrate are processed during the day. For this reason, a higher value of this parameter positively affects the business.

Furnaces for copper metallurgy work at high temperatures, so they must be protected from the inside since they are in contact with the reaction medium and smelting products. The inside of a furnace is made of refractory bricks, which isolate high-temperature zones and reduce heat losses, thus ensuring the static stability of the furnace, etc. In certain parts of the furnace (for chemical reaction) that are used for the separation of matte from slag as well as for the separation of gases, different technological conditions prevail, so a variety of refractory materials and different ways of protecting the device by water-cooling are required. The wall lining in all types of autogenic furnaces is mainly made of chrome-magnesite bricks. The exception is the Inco flash furnace, which reaches extremely high temperatures, so copper-cooling water jackets for flash furnaces are built into its walls. Previously, the chimney for flash smelting was made of refractory bricks. Over the last decades, there has been a tendency to entirely cool chimneys with water-cooling off-gas devices to change dust into a solid before entering the boiler. While assigning ranking based on this parameter, priority should be given to smelters with a longer lining lifetime. This reduces the direct costs arising from the lining change and the time workers spend on the lining change. Moreover, the indirect costs of production stagnation are reduced, as is the negative impact on the environment, reflected through dust resulting from poor cooling of the off-gases.[17–19,24,33]

A significant parameter is also the percentage of sulphur and copper recovery. The sulphur and copper recovery should be maximised to increase the economy of the technological process. In addition to economic reasons, environmental ones have become dominant in selecting a technological process.

Also, it has been noticed that the content of Fe in copper is always low so that the content of copper is high, and thus, a smaller extent of further refining is needed. Also, the content of Cu in the slag should be at the lowest possible level so that the copper recovery is better. Copper technological processes have the advantage of being capable of smelting poor concentrates, thus increasing the number of potential concentrate suppliers.[21,34,35] Copper smelting facilities worldwide use many different pyrometallurgical processes to extract copper.[3,17,24] Each technology exhibits different positives and negatives based on the above-described parameters and characteristics. The eight most current and representative technological processes were selected for further consideration (**Table 1**). The technological processes represent alternatives in this study.

According to the data from the USGS website (the data are for 2023), there are over a hundred operational copper smelters worldwide. The largest number of copper smelters are located in China (19 smelters), Russia (10 smelters), Chile (7 smelters) and Japan (6 smelters). Regarding the application of technology, the most widespread is the reverberatory furnace (31 smelters use this technology), followed by Outokumpu flash smelting (Outotec) (24 smelters use this technology). In contrast, the least applied technologies are Inco Flash (one smelter in the USA and one in Canada) and Vanyukov (one smelter in Russia and one in Kazakhstan). The technological process called Ausmel/Isasmelt lance is currently utilised by seven smelters worldwide, El Teniente by six smelters, while Noranda and Mitsubishi are each used in

Table 1: Brief overview of the considered processes of pyrometallurgical extraction of copper

Type of the process	Major positives	Literature review
Outokumpu flash smelting (Outotec)	adaptability, low energy consumption, high sulphur recovery, more efficient use of sulphide energy from concentrates, higher utilisation of metals and much better protection of the atmosphere against pollution by SO_2 and other harmful substances	Higgins et al., 2009;[36] Vračar, 2010;[33] Schlesinger et al., 2011;[19] Liu et al., 2014;[37] Outokumpu, 2023;[38] Outotec, 2023;[39] USGS, 2023;[40]
Ausmel/Isasmelt lance	highly efficient process, low production costs, compliance with strict environmental standards	Davenport et al., 2002;[24] Schlesinger et al., 2011;[19] Najdenov et al., 2012;[25] USGS, 2023;[40] Isasmelt, 2023;[41]
Inco Flash	using technical oxygen instead of air reduces the amount of gases produced; however, this method is still quite costly with a large consumption of electricity	[42]Queneau and Marcuson, 1996; Moskalyk and Alfantazi, 2003;[17] Kapusta, 2004;[18] Vračar, 2010;[33] Inco, 2023;[43]
Mitsubishi	high utilisation of SO_2, reduction of the emission of harmful gases, high flexibility, ability to process reverse and secondary materials, reduced consumption of electricity	Shibasaki et al., 1993;[44] Iida et al., 1997;[45] Asaki et al., 2001;[46] Davenport et al., 2002;[24] Fthenakis et al., 2009;[47] Schlesinger et al., 2011;[19] Wang et al., 2013;[48]
Noranda	small amount of fuel, possibility to achieve complete autogenic smelting with 40% of oxygen, but with a negative economic effect	Veldbuizen and Sippel, 1994;[49] Davenport et al., 2002;[24] Cui and Zhang, 2008;[50] Vračar, 2010;[33] Schlesinger et al., 2011;[19]
El Teniente	better energy use, economic, but it requires a more complicated and complex control	Bergh et al., 2005;[51] Valencia et al., 2006;[52] Schaaf et al., 2010;[53] Najdenov et al., 2012;[25] Najdenov, 2013;[20]
Vanyukov	(semi)autogenic smelting of copper concentrates with various additives, large-folded and selectively digested rich copper ore, return materials and the solvent	Davenport et al., 2002;[24] Moskalyk and Alfantazi, 2003;[17] Schlesinger et al., 2011;[19] Najdenov et al., 2012;[25]
Reverberatory furnace	it is often replaced by some of the previous ones because it does not have many positives and it requires high energy consumption	Diaz et al., 1991;[54] Ullmann, 1995;[55] Stanković, 2000;[56] Davidović et al., 2009;[57] Najdenov et al., 2013;[20] Mohagheghi and Askari, 2016;[58] USGS, 2023;[40]

four smelters. Based on the data from Kapusta's[18] study, which depicts roughly half of the smelters with different types of technological processes, it can be concluded that the ratio of the applied copper extraction technological processes has not significantly changed in the past 20 years.[18,40]

3 METHODOLOGY

The aim of this research was to select the optimal technological process of copper extraction in complex conditions. To fulfil this aim, authors developed a hybrid fuzzy AHP-TOPSIS model. The FAHP method was used to assess the weight of factors based on the experts' evaluation of each criterion's significance, while the TOPSIS method was used to rank the technological processes. The prioritisation process used in this research is presented in **Figure 1**. The applied methods are briefly described below.

3.1 Fuzzy AHP

AHP is one of the most used MCDA methods. This method was introduced in 1980 by Saaty, and since then, the number of studies in which this method was applied has continually increased. The main reason for this popularity is its ease of operation and application as well as its great flexibility. Thanks to these characteristics, this method is applied in many areas, such as economics, manufacturing, social science, education, etc.[59–64] However, problems in applying this method may arise from using experts' subjective judgments during evaluations.[65] In fact, experts use exact values when comparing criteria or alternatives and therefore cannot express their preferences.[66] This problem was recognised by Laarhoven and Pedrycz (1983), who proposed the FAHP (fuzzy analytical hierarchy process) method as the solution to this problem. The FAHP uses the principles of fuzzy logic within the AHP method.[67,68]

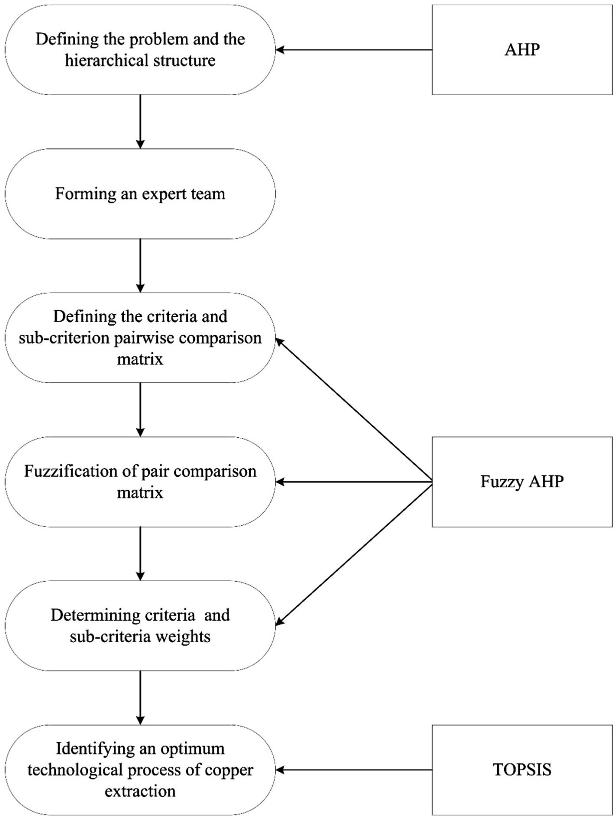


Figure 1: Proposed approach

There are many variants of the FAHP method. In this research, modified Chang's extent analysis was applied to prioritise copper smelting processes. This modification includes using triangular fuzzy numbers (TFNs) for the pairwise comparison scale and the extent analysis method for the synthetic extent value of Si of the pairwise comparison.[69] The main flaw of modified Chang's extent analysis is that determined weights cannot be used as priorities because they do not represent the relative importance of decision criteria or alternatives. Wang and Chen (2007) corrected the normalisation formula to solve this problem.[70,71] The FAHP method used in this research is described in several steps.

Step 1: Defining the problem and developing a fuzzy comparison matrix. A hierarchical structure of an AHP problem consists of at least three levels. At the top of this structure, there is an overall goal of the problem, in the middle, there are multiple criteria, while at the bottom there are decision options.[68] Decision-makers evaluate the relative significance of particular criteria and alternatives at each hierarchical level in pairs, with the help of linguistic variables. In this way, paired comparison matrices are defined, whose values are translated into TFNs in accordance with **Table 2** to obtain a fuzzy pairwise comparison matrix. This completes the first step of Chang's (1996) extent analysis method.[69,72,73]

Table 2: Linguistic variables for pairwise comparison of each criterion[73,74]

Linguistic variables	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally strong	(1, 1, 1)	(1, 1, 1)
Moderately strong	(2, 3, 4)	(1/4, 1/3, 1/2)
Strong	(4, 5, 6)	(1/6, 1/5, 1/4)
Very strong	(6, 7, 8)	(1/8, 1/7, 1/6)
Extremely strong	(9, 9, 9)	(1/9, 1/9, 1/9)
Intermediate values	(1, 2, 3)	(1/3, 1/2, 1)
	(3, 4, 5)	(1/5, 1/4, 1/3)
	(5, 6, 7)	(1/7, 1/6, 1/5)
	(7, 8, 9)	(1/9, 1/8, 1/7)

Step 2: Determining the fuzzy synthetic extent # with respect to criteria *i* that is carried out according to Kabir and Sumi, 2014:

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{C}_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{C}_{ij} \right]^{-1}, \quad i = 1,2,\dots,n \tag{1}$$

where *n* represents the size of the fuzzy judgment matrix.[75]

An inverse vector from the preceding equation can be calculated using the following formula:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\widetilde{C}_{ij}\right]^{-1}=\left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n}u_{ij}},\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n}m_{ij}},\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n}l_{ij}}\right) \tag{2}$$

However, as already stated, Wang and Chen (2007)[70] corrected the normalisation formula according to the following form:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\widetilde{C}_{ij}\right]^{-1}=\left(\frac{1}{\sum_{i=1}^{n}l_{ij}+\sum_{k=1,k\neq i}^{n}\sum_{y=1}^{n}u_{ij}},\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n}m_{ij}},\frac{1}{\sum_{y=1}^{n}u_{kj}+\sum_{k=1,k\neq i}^{n}\sum_{y=1}^{n}l_{kj}}\right) \tag{3}$$

Since normalised degrees of probability can indicate the extent to which a given TFN is greater than any other TFN, but not their relative significance, Liou and Wang (1992)[76] proposed a total integral value with an index of optimism *a*, which gives priorities to the synthetic extent values according to the following equation:[75]

$$I_{T}^{a}(\widetilde{s}_{l})=\frac{1}{2}a(m_{i}+u_{i})+\frac{1}{2}(1-a)(l_{i}+m_{i})=\frac{1}{2}\left[au_{i}+m_{i}+(1-a)l_{i}\right] \tag{4}$$

The optimism index *a*, in fact, represents the degree of optimism of the decision maker and ranges from 0 to 1. If the optimism index is closer to 1, the decision maker is more optimistic, and the opposite; if the index of optimism index is closer to 0, the decision maker is more pessimistic.[77]

Step 3: Determination of the normalised weight vector $W = (w_1, w_2, ..., w_n)^{\mathrm{T}}$ fuzzy judgment matrix is done using the following formula:[77]

$$w_{x}=\frac{I_{T}^{a}(\widetilde{S}_{x})}{\sum_{k=1}^{n}I_{T}^{a}(\widetilde{S}_{k})} \tag{5}$$

where w_x represents a non-fuzzy number.

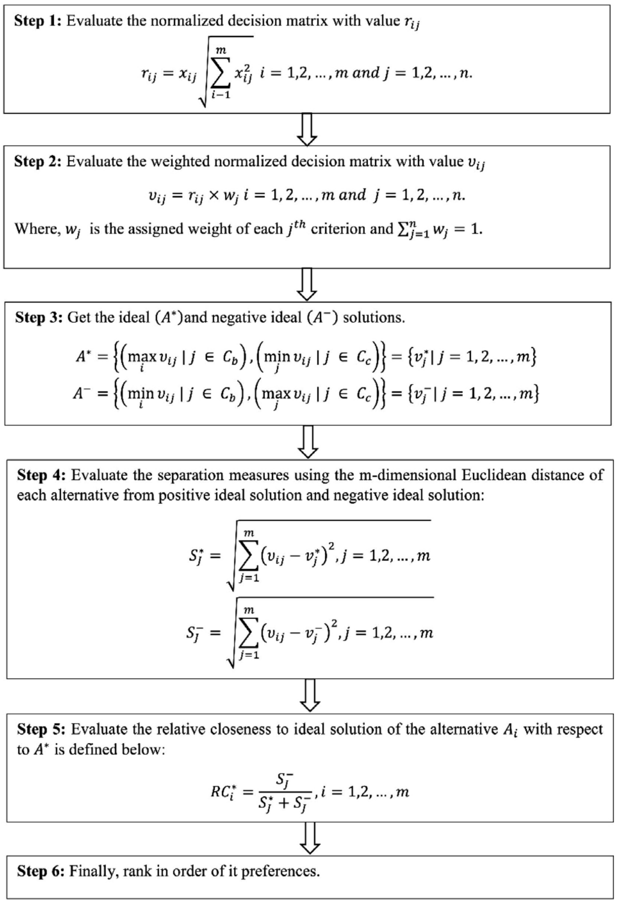
3.2 TOPSIS

Another MCDM method used in this research is the technique for order of preference by similarity to ideal solution (TOPSIS). This method was introduced by Hwang and Yoon in 1981. The main characteristic of this method is that the best alternative has the shortest distance from the positive ideal solution (PIS) and the longest distance from the negative ideal solution (NIS).[78] A positive ideal solution represents a solution that maximises the benefit attributes and minimises cost attributes. On the other hand, a negative ideal solution maximises the cost attributes and minimises the benefit attributes.[79] The TOPSIS method has been widely used to solve the ranking problems in real-life situations, thus providing an easily understandable and programmable calculation process. This method has the ability to consider different criteria with different units simultaneously.[80] In addition, to enable the application of this method, the values of the chosen criteria used for the selection must be numerically, monotonically rising or decreasing, and they must also be organised in the form of proportional units.[81] However, despite its popularity and simplicity, this method is often criticised for its inability to adequately handle the uncertainty and imprecision in value assignment by the decision maker.[82] As a solution, the TOPSIS method has undergone numerous upgrades to adequately solve the problems of ranking and justification of the results obtained.[83,84]

The procedure of the TOPSIS methodology is described by Hwang and Yoon (1981) and shown in **Figure 2**.

4 RESULTS AND DISCUSSION

The previous section describes the multi-criteria decision-making tools as well as mathematical methods that



Step 1: Evaluate the normalized decision matrix with value r_{ij}

$$r_{ij}=x_{ij}\sqrt{\sum_{i-1}^{m}x_{ij}^{2}}\quad i=1,2,\dots,m\ and\ j=1,2,\dots,n.$$

Step 2: Evaluate the weighted normalized decision matrix with value v_{ij}

$$v_{ij}=r_{ij}\times w_{j}\quad i=1,2,\dots,m\ and\ \ j=1,2,\dots,n.$$

Where, w_j is the assigned weight of each j^{th} criterion and $\sum_{j=1}^{n}w_j=1$.

Step 3: Get the ideal $(A^{*})$and negative ideal (A^{-}) solutions.

$$A^{*}=\left\{\left(\max_{i}v_{ij}\mid j\in C_{b}\right),\left(\min_{j}v_{ij}\mid j\in C_{c}\right)\right\}=\{v_{j}^{*}\mid j=1,2,\dots,m\}$$
$$A^{-}=\left\{\left(\min_{i}v_{ij}\mid j\in C_{b}\right),\left(\max_{j}v_{ij}\mid j\in C_{c}\right)\right\}=\{v_{j}^{-}\mid j=1,2,\dots,m\}$$

Step 4: Evaluate the separation measures using the m-dimensional Euclidean distance of each alternative from positive ideal solution and negative ideal solution:

$$S_{j}^{*}=\sqrt{\sum_{j=1}^{m}\left(v_{ij}-v_{j}^{*}\right)^{2}},j=1,2,\dots,m$$
$$S_{j}^{-}=\sqrt{\sum_{j=1}^{m}\left(v_{ij}-v_{j}^{-}\right)^{2}},j=1,2,\dots,m$$

Step 5: Evaluate the relative closeness to ideal solution of the alternative A_i with respect to A^{*} is defined below:

$$RC_{i}^{*}=\frac{S_{j}^{-}}{S_{j}^{*}+S_{j}^{-}},i=1,2,\dots,m$$

Step 6: Finally, rank in order of it preferences.

Figure 2: Stepwise procedure of TOPSIS[78]

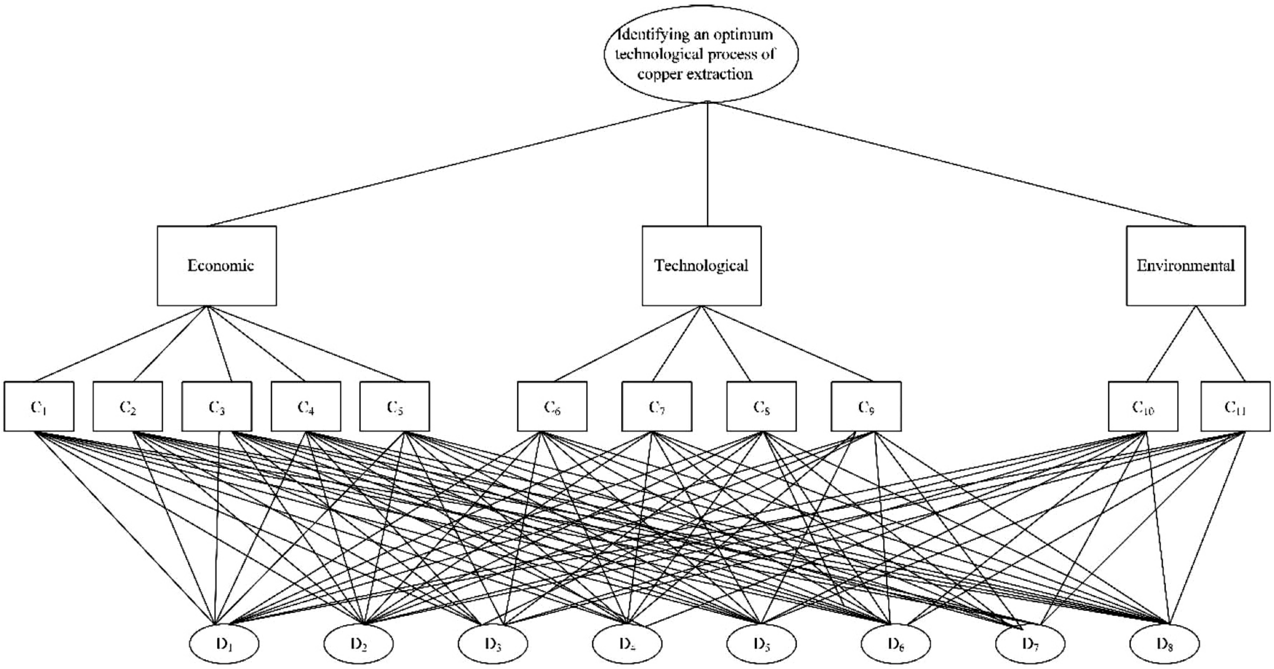


Figure 3: Hierarchical structure of the problem

were used to support this research. In this way, the basis for solving the defined research problem in this study is established. The next step is the implementation of the defined methodology, which creates a possibility of achieving the basic goal of this research, i.e., determining which of the current technological processes for copper extraction is the best at achieving the optimal production goals.

The implementation of the proposed methodology consists of six steps, as shown in **Figure 1**. Due to a limited space, it does not show the procedure and calculations for each step, but it provides general information so that research and its results can be followed more easily.

The first step of the proposed methodology consists of defining the hierarchical structure of the problem. The hierarchical structure of the problem is shown in **Figure 3**.

At the top of the hierarchical structure is the goal for the problem solution. In this case, it is identifying the optimum technological process for copper extraction. The criteria used in the ranking are at the second level. The evaluation was carried out based on three types of criteria: economic, technological and environmental. The selection of these three criteria was based on the literature that deals with the impact of these factors on copper smelters.[85–87] Perez et al.,[85] in their research conducted in Chile, one of the leading countries in copper production in the world, made the same division of criteria into environmental, economic and technological factors affecting Chilean copper smelters. There are several sub-criteria at the third level used for defining each criterion. Since some sub-criteria can be included in more than one criterion, the division in our work was done based on the possibility that certain sub-criteria significantly influence certain segments of the chosen criteria. Thus, certain sub-criteria are classified as economic, even though they are technological in nature because they significantly affect the profitability of a copper smelter. On the other hand, other sub-criteria undoubtedly belong to the defined criteria. The order of criteria and their sub-criteria is as follows:

ECONOMIC CRITERIA
C_1 – Concentrate amount in charge (t/day)
C_2 – Production of copper matte (t/day)
C_3 – Campaign life (year)
C_4 – Copper recovery (%)
C_5 – Cu content in waste slag (%)
TECHNOLOGICAL CRITERIA
C_6 – Cu content range in the concentrate
C_7 – Cu content in copper matte (%)
C_8 – Fe content in matte (%)
C_9 – Minimal Cu content in the concentrate
ENVIRONMENTAL CRITERIA
C_{10} – Production of waste slag (t/day)
C_{11} – Sulfur recovery (%)

Based on a comprehensive literature review conducted by Nikolić et al.[21] and relevant secondary sources listed in **Table 1**, data was collected for a complete ranking of the eight copper extraction technologies based on the proposed criteria as presented in **Table 3**.[18,21]

In the next step of the analysis, a group of experts composed of several university professors and engineers dealing with copper smelters was formed to define the initial matrices of the pairwise comparison criteria concerning the defined goal and the sub-criteria relative to the criteria. In this way, group decision-making using the AHP allows multiple stakeholders to express their opin-

Table 3: Values of parameters for ranking copper extraction technologies[3]

Criterion Alternatives	Concentrate amount used (t/day)	Cu content range in the concentrate (%)	Cu content in copper matte (%)	Fe content in matte (%)	Production of waste slag (t/day)	Production of copper matte (t/day)	Campaign life (year)	Sulphur recovery (%)	Copper recovery (%)	Cu content in waste slag (%)	Minimal Cu content in the concentrate (%)
Outokumpu flash	2750	5	65	11.5	2025	1500	9	96	97	0.65	26
Ausmelt/Isasmelt lance	2250	4	67	14	1210	1200	2.1	97	97	0.6	25
Inco flash	3000	9	50	15	1350	935	15	93.6	97.5	0.65	20
Mitsubishi	2150	6	71.5	7.75	1375	1209	3	99.5	97	0.75	28
Noranda	2250	9	72.5	4.5	1500	975	1.75	94	95	0.75	28
El Teniente	2300	7	73	4.5	1725	962.5	1.5	90	96	0.325	26
Vanyukov	2150	8	59.5	10.5	1750	1300	4.5	90	98	0.6	26
Reverberatory	2000	16	40	27.5	1050	1450	3.5	50	93	0.75	19

Table 4: Level of criteria

Level of criteria	Environmental			Technological			Economic		
	L	M	U	L	M	U	L	M	U
Environmental	1	1	1	1	2	3	1	2	3
Technological	1/3	1/2	1	1	1	1	1	1	1
Economic	1/3	1/2	1	1	1	1	1	1	1

Table 5: Sub-criterion level: environmental level

Environmental level	Production of waste slag (t/day)			Sulphur recovery (%)		
	L	M	U	L	M	U
Production of waste slag (t/day)	1	1	1	1/6	1/5	1/4
Sulfur recovery (%)	4	5	6	1	1	1

Table 6: Sub-criterion level: technological level

Technological level	Cu content range in the concentrate			Cu content in copper matte (%)			Fe content in matte (%)			Minimal Cu content in the concentrate		
	L	M	U	L	M	U	L	M	U	L	M	U
Cu content range in the concentrate	1	1	1	1/4	1/3	1/2	1/4	1/3	1/2	1	2	3
Cu content in copper matte (%)	2	3	4	1	1	1	2	3	4	2	3	4
Fe content in matte (%)	2	3	4	1/4	1/3	1/2	1	1	1	2	3	4
Minimal Cu content in the concentrate	1/3	1/2	1	1/4	1/3	1/2	1/4	1/3	1/2	1	1	1

ions on the importance of the chosen criteria. To determine individual preferences, decision-makers provide pairwise comparison matrices. These matrices are used for obtaining independent preferences in the first round. These preferences are then aggregated, using aggregation through consensus voting on judgments in the second round.[88] This method of aggregating individual preferences was chosen to simplify the judging process as it can better reflect real-world decision-making.[89] Additionally, the consistency of all aggregated matrices of the pairwise comparison was checked when all matrices showed consistency with values of CR<0.1 (level of criteria CR=0, environmental level CR=0, technological level CR=0.0810 and economic level CR=0.0291). Then, fuzzification of the pairwise comparison matrix was done. The results of this step are shown in **Tables 4** to **7**. In these tables, L represents the smallest possible value, M represents the expected value, and U represents the highest possible value that describes the TFN.

In the next step, using the above FAHP methodology, the local and overall significance of the sub-criteria and criteria are determined. The results of this part of the analysis are shown in **Table 8**.

The obtained overall significance of the sub-criteria represents the weight coefficient of the criteria used in ranking the technological processes with TOPSIS, which

Table 7: Sub-criterion level: economic level

Economic level	Concentrate amount used (t/day)			Production of copper matte (t/day)			Campaign life (year)			Copper recovery (%)			Cu content in waste slag (%)		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
Concentrate amount used (t/day)	1	1	1	2	3	4	2	3	4	1/4	1/3	1/2	1/3	1/2	1
Production of copper matte (t/day)	1/4	1/3	1/2	1	1	1	1	1	1	1/4	1/3	1/2	1/4	1/3	1/2
Campaign life (year)	1/4	1/3	1/2	1	1	1	1	1	1	1/6	1/5	1/4	1/4	1/3	1/2
Copper recovery (%)	2	3	4	2	3	4	4	5	6	1	1	1	1	1	1
Cu content in waste slag (%)	1	2	3	2	3	4	2	3	4	1	1	1	1	1	1

Table 8: Local and overall significance of criteria and sub-criteria

Criterion	Criterion significance	Sub-criterion	Local sub-criterion significance	Overall sub-criterion significance
Environmental	0.492	C10	0.1690	0.0831
		C11	0.8310	0.4086
Technological	0.254	C6	0.1629	0.0414
		C7	0.4206	0.1069
		C8	0.3144	0.0799
		C9	0.1021	0.0259
Economic	0.254	C1	0.2100	0.0534
		C2	0.0837	0.0213
		C3	0.0802	0.0204
		C4	0.3575	0.0909
		C5	0.2686	0.0683

Table 9: Weights of selected criteria and their directions

Criterion Alternatives	Concentrate amount used (t/day)	Cu content range in the concentrate (%)	Cu content in copper matte (%)	Fe content in matte (%)	Production of waste slag (t/day)	Production of copper matte (t/day)	Campaign life (year)	Sulphur recovery (%)	Copper recovery (%)	Cu content in waste slag (%)	Minimal Cu content in the concentrate (%)
w-weight	0.0534	0.0414	0.1069	0.0799	0.0831	0.0213	0.0204	0.4086	0.0909	0.0683	0.0259
Min/Max	Max	Max	Max	Min	Min	Max	Max	Max	Max	Min	Min

is also the next step of the analysis. **Table 9** gives the weights of the selected criteria and their directions. During this ranking, a complete ranking of all the technological processes was performed.

Table 10: Ranking of technological processes based on relative closeness to the ideal solution

Criterion Alternatives	CI *	RANK
Outokumpu flash	0.7268	4
Ausmelt/Isasmelt lance	0.7081	5
Inco flash	0.7079	6
Mitsubishi	0.7554	1
Noranda	0.7528	2
El Teniente	0.7350	3
Vanyukov	0.6843	7
Reverberatory	0.2051	8

After applying all the steps of the TOPSIS methodology, described in the previous section, to the data set provided in **Tables 3** and **9**, a list of the technological processes based on determining the relative closeness to an ideal solution is shown in **Table 10**. The alternative with a higher value is ranked better with this methodology.

Based on **Table 10**, it can be concluded that the best ranked technology is Mitsubishi. It is followed by Noranda, El Teniente, Outokumpu flash, Ausmelt/Isasmelt lance, Inco flash and Vanyukov, in that order. Reverberatory is at the bottom of the ranking. As can be noticed through the evaluation of the significance by the experts, the greatest priority was given to one environmental parameter, "Sulphur recovery", which was significantly higher than any economic or technological parameter. All technologies based on autogenous processes are more environmentally acceptable and economically justified. On the other hand, the reverberatory furnace has become out of date, so it should no longer be used. In the case of high-tech technology, sulphur recovery has the major impact, which is 99.5 %.

5 CONCLUSIONS

Copper production represents one of the crucial industrial sector activities that contributes to each country's economic development. When constructing a copper extraction plant, implementing a technological process that will give the best economic effects and be environmentally acceptable is required. The decision on the optimal copper extraction process that will be applied is very complex due to a number and the nature of criteria that must be considered. Also, numerous participants in the decision-making process can have different interests, so priorities and the weight of the selected criteria should be differentiated. All of the above conditions should be respected and in compliance with the company's strategy. As Pivodová et al.[90] stated, a lack of a systematic approach is the main cause of shortcomings in achieving the set goals. This research provides a basis for systematically managing a new copper extraction plant.

Based on this research, a very efficient model for solving the above problems was created. Namely, the presented complex methodology enables a detailed analysis of the problems and significantly accelerates the decision-making process when constructing this kind of plant.

The best-positioned technological process in this study is Mitsubishi. This technological process is dominant over the others based on the criteria such as sulphur and copper recovery. The values of these two parameters are very high, but the other observed criteria are optimal. In addition to the values of the criteria adopted for the final prioritisation, expert preferences also have a significant impact since group decision-making based on subjective assessments of decision-makers is not free from bias. Different expert preferences on the criteria can give different results. Hence, the final prioritisation of the smelting processes may be different in another research based on the experts' preferences and adopted criteria. However, an increased interest in the ecology of smelting facilities is also reflected in the results of this research. Comparing the obtained results with the results of some previous studies published by Moskalik and Alfantazi,[17] Kapusta,[18] Nikolić,[21] Perez et al.,[85] Aleksandar et al.[86] and Sourabh et al.,[87] we can see that the trend of adopting technologies that are environmentally acceptable and economically justifiable continues.

Using this model to decide on the application of a new technological process gives us an overall picture of all the advantages of one alternative over the other, taking into account all the criteria considered. However, despite the implementation of the model, the final decision remains with the decision-makers. The goal of this model is to make the management mechanism and decision-making process more efficient and the solutions optimal.

In the future, the authors will work on further improvements of this kind of methodology, which combines several approaches and tools, integrating positive impacts of each approach and neutralising the shortcom mings. In this way, decision-makers are given the opportunity to justify their decision about the advantages of a particular alternative over the others with more arguments.

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