Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Simplified model supporting decision-making considering the criteria of sustainable development and life cycle assessment (LCA)

Andrzej PACANA[1]*, *Dominika SIWIEC*[2], *Lucia SPRINC*[3] and *David KRASNICI*[4]

Authors' affiliations and addresses:
[1,2] Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, al. Powstancow Warszawy 12, 35-959 Rzeszow, country: Poland
e-mail: app@prz.edu.pl
e-mail: d.siwiec@prz.edu.pl

[3,4] Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University of Košice, Letná 9, 042 01 Košice
country: Slovakia
e-mail: lucia.sprinc@tuke.sk
e-mail: david.krasnici@tuke.sk

***Correspondence:**
Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, al. Powstancow Warszawy 12, 35-959 Rzeszow, country: Poland
tel.: +48 17 86 51 390
e-mail: app@prz.edu.pl

Funding information:
Visegrád Fund, project ID: 22230264

Acknowledgement:
The article was created as part of research conducted in the project Visegrád Fund, project ID: 22230264, Title: Qualitative-environmental aspects of products improvement, carried out from February 1, 2023 to January 31, 2024: Applicant: Politechnika Rzeszowska im. Ignacy Łukasiewicz. Rzeszow University of Technology, Rzeszów, PL.

How to cite this article:
Pacana, A., Siwiec, D., Sprinc, L. and Krasnici, D. (2023). Simplified model supporting decision-making considering the criteria of sustainable development and life cycle assessment (LCA). *Acta Montanistica Slovaca*, Volume 28 (2), 408-423

DOI:
https://doi.org/10.46544/AMS.v28i2.12

Abstract
Sustainability is at the heart of continuous product improvement, where social, environmental, and economic considerations are key. This is a difficult task, especially in the area of the following economic and environmental changes, as well as changes in customer expectations. Additionally, it has become crucial to make product decisions that will be based on their entire life cycle (LCA). Although these aspects of sustainability and LCA are popular, bringing them together in one analysis remains challenging. Therefore, the article's objective was to develop a simplified model that supports decision-making, taking into account the criteria of sustainable development and life cycle assessment (LCA). The originality is the proposed model, which operates based on a qualitative indicator (product quality level), an environmental indicator (the product's impact on the environment throughout its life cycle) and a price indicator (purchase price of the product). These indicators are created using the TOPSIS method and the modified ACJ-E method. As a result, a product ranking is created. A novelty is the combination of Life Cycle Assessment (LCA) criteria with quality criteria and the actual purchase price of the product. The model test was carried out on the example of CATERPILLAR mini excavators. However, the model can be dedicated to any company that wants to make decisions in accordance with the idea of sustainable development.

Keywords
sustainable development, life cycle assessment, LCA, quality, decision-making, TOPSIS, price, mechanical engineering, production engineering

Introduction

The negative impact of the mining industry on climate change, human health, and ecosystems is due to the extensive use of fossil fuels (Capony et al., 2012; Tej et al., 2014; Chapčáková et al. 2022). Therefore, as the authors indicate (Hilson & Murck, 2000), it is extremely important to analyse the extractive industry in the area of sustainable development. It is difficult, for example, in the area of environmental management, social performance, or when improving planning processes and implementing tools supporting the development of these organisations, taking into account economic aspects (Bogusz & Sulich, 2020; Kristóf & Virág, 2022; Pacana & Siwiec, 2021). Furthermore, it is problematic to clearly determine whether mining (mainly branches other than fossil fuels) can support the achievement of the Sustainable Development Goals (SDGs) (Dolinayova & Domeny, 2022; Karas, 2022; Gavurova et al., 2021, 2022).

Modern mining companies, which also implement corporate social responsibility (CSR), have the greatest impact on the development of sustainable development in this industry. These activities mainly aim to reduce the impact on the natural environment, including reducing risk. According to (Bogusz & Sulich, 2020; Bogusz Ahmadet al., 2021; Wang et al., 2023; Kravcakova Vozarova et al. 2022), enterprises should create such an organisational context to use innovations, including creating ecosystems, while strengthenin society's economic value and satisfaction. Furthermore, as the authors indicate (Adiansyah et al., 2015), it is advisable to implement a strategy for the management of mining waste to protect the environment and society against their negative factors (Khalilsanjani et al., 2021; Pacana & Siwiec, 2022b, Rybárová et al., 2022).

However, production growth, mainly from lower-grade ores in mines, continues to increase. The presented issue is part of the product life cycle area, which is a tool for identifying and quantifying potential environmental burdens (Calado et al., 2019; Ahmad et al., 2022). According to the ISO 14040 standard, it is a set of procedures and studies of input and output data that are determined on the basis of materials and energy with their environmental impact throughout the life cycle (from resource extraction and transformation to final disposal, including the stages of production and use). According to the authors of the articles (Calado et al., 2019; Lagerstedt et al., 2003), LCA in the mining industry can be used in various ways, for example, to provide social data or to assess environmental performance, identify hot spots or analyse technical data.

However, as presented by the authors of the articles (Adiansyah et al., 2015; Awuah-Offei et al., 2011; Suppen et al., 2006), the use of LCA in the mining industry is not often analysed. For example, in the article (Burchart-Korol et al., 2016), an environmental assessment of hard coal mining activities was performed while taking into account direct and indirect factors related to raw materials production and energy in processes. In turn, the article (Blengini et al., 2012; Androniceanu, 2023) proposes a methodology for analysing the efficiency of recycled resources in the context of a sustainable mix of aggregates. The analyses were supported by LCA.

Another aspect in the context of sustainable development, but also life cycle assessment, is the economic analysis, in which, for example, life cycle costing (LCC - Life Cycle Costing) is used. However, the LCC methodology is not sufficiently standardised. Therefore, its use as a decision-making tool is much more difficult. In addition, as the authors of the article point out (Lagerstedt et al., 2003; Belas et al., 2019), the production of sustainable products often requires significant changes, which are introduced as part of the process of improving (so-called rethinking) products and systems. In this context, the authors of the articles (Damigos, 2006; Durocher & Putnam, 2013; Nicolas et al., 2020; Valderrama et al., 2020; Fulajtárová & Gavura, 2022) considered the actual purchase price of selected resources for investments in mining and economic expectations.

After a review of the literature on the subject, it was concluded that the analyses were performed in the context of sustainable development and LCA in the mining industry. The environmental impact was studied, the requirements of society were taken into account, and analyses were carried out taking into account resource prices. However, these aspects were not analysed coherently and simultaneously. This was considered a research gap. Therefore, the objective was to develop a simplified model that supports decision making taking into account the criteria of sustainable development and LCA.

The originality is the proposed model, which works on the basis of a qualitative indicator (product quality level), an environmental indicator (the product's environmental impact throughout its life cycle) and a price indicator (purchase price of the product). What is new is the combination of LCA criteria with quality criteria and the actual purchase price of the product. The model study was conducted using the example of CATERPILLAR mini excavators.

Material and Methods

The model concept concerns the entity's support (for instance, expert, broker, or company manager) in selecting a satisfactory product. It was assumed that satisfaction refers to meeting the needs for the quality of the product, its impact on the natural environment in the life cycle, and the cost of purchasing this product. Quality is its efficiency, which is presented by the basic criteria of the product (included in the product catalogue). The environmental impact covers the product's environmental impact throughout the product life cycle, from sourcing materials to disposal. In turn, the purchase cost is the total cost that is incurred when purchasing the product expressed in the appropriate currency. This is a simplified model that takes into account only expert assessments. The model does not implement real environmental impact values. The algorithm of the proposed model is shown in Figure 1.

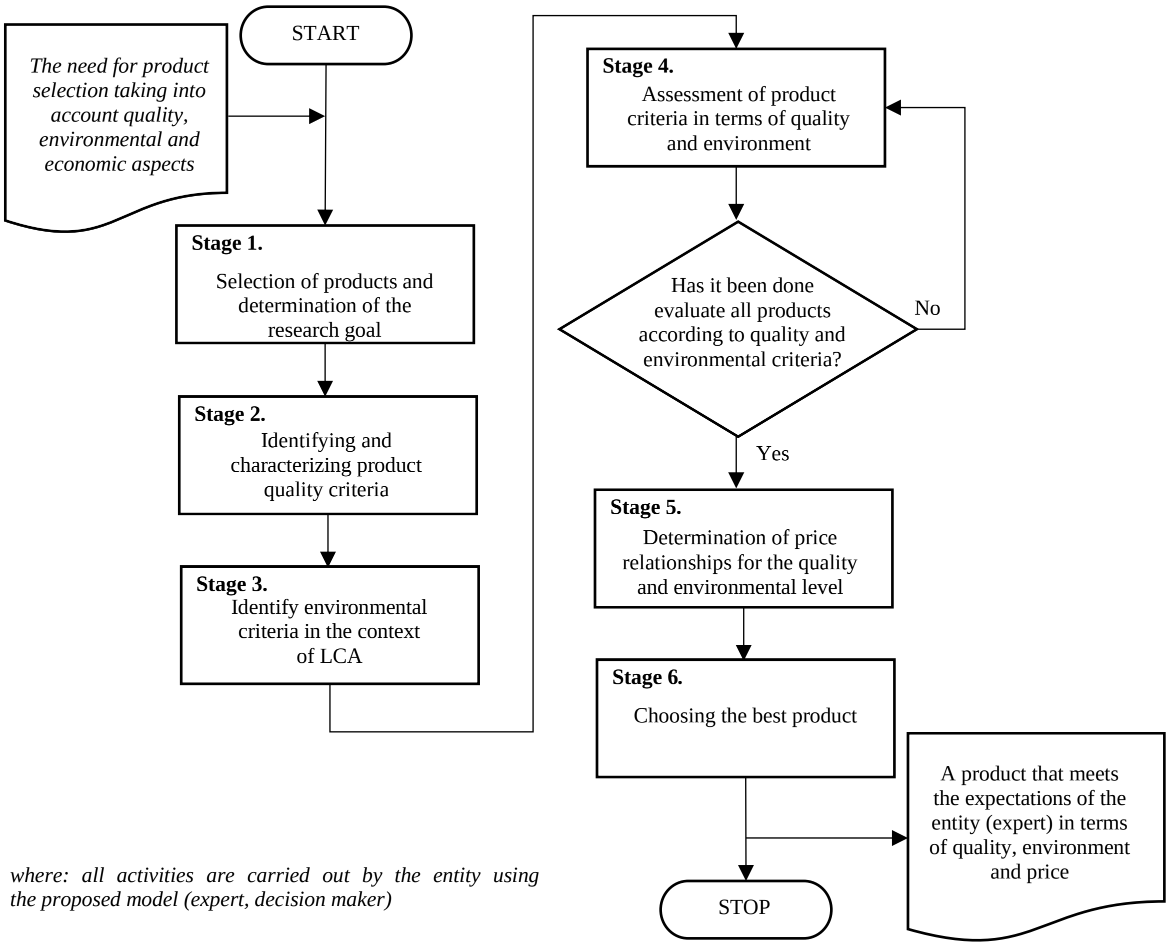

Fig. 1. Product selection algorithm in terms of quality, environmental and price aspects.

The characteristics of the stages of the model are presented in the further part of the study.

Stage 1. Selection of products and determination of the research goal

Under the proposed model, the entity (offerer, broker, expert) makes the selection of products for analysis. The choice depends on the individual preferences of the entity, e.g. existing supplies or anticipated production demand. It is necessary to analyse one type of product, e.g., the same or different manufacturers. According to the literature on the subject, it is effective to analyse no more than nine products at the same time (Ostasz, Siwiec, & Pacana, 2022b; Pacana & Siwiec, 2022a). For analysis purposes, these products can be marked with symbols to not suggest a result to experts (i.e. to reduce subjectivity).

After selecting the products, it is necessary to define the purpose of the research. This is done by an expert (entity) using the proposed model. In the proposed approach, the goal should be the possibility of choosing a product that will be satisfactory for the expert (entity, enterprise) in terms of quality (product performance) and environmental (low impact on the environment throughout the life cycle) and price (relatively low purchase price/cost). To determine the purpose of the analysis, it is possible to use the SMART(-ER) method, as presented in the literature, e.g. (Lawor & Hornyak, 2012).

Stage 2. Identifying and characterising product quality criteria

As part of the analysis, defining the quality criteria for selected products is necessary. These criteria are selected by an expert (entity) according to the catalogue of these products. Qualitative criteria are those that affect the performance of the product, i.e. they relate to satisfaction with its use. Criteria can be measurable or nonmeasurable. Their number should range from about 5 to a maximum of 9 criteria, according to the authors of the papers, e.g. (Saaty, 2003; Saaty & Tran, 2007; Siwiec & Pacana, 2022). Based on these criteria, the quality assessment of selected products will be carried out. Therefore, all criteria should be adequately characterised for the selected products. It can be a specific value, a range of values, or a description. This information is usually contained in product catalogues (specifications). The results from this stage can be saved in a table, where the rows are products, and the columns are the criteria and their parameters.

Stage 3. Identify environmental criteria in the context of LCA

In order to analyse the impact of products on the natural environment throughout their life cycle (LCA), a simplified verification was adopted. This means making life cycle assessments of products without taking into account quantitative interpretations of environmental impacts, where these assessments are based on the knowledge and opinion of a panel of experts. Therefore, a team of experts evaluates the negative impact of products on the environment, taking into account the key environmental criteria that occur at individual stages of the life cycle (LCA). The evaluation of products in terms of environmental criteria in the context of LCA is made in the later stages of the model.

For this reason, the team of experts determines the environmental impact criteria that will be appropriate for the analysed research object (product). Environmental criteria mean the negative impact of these products throughout their life cycle. Environmental criteria are selected by a team of experts during brainstorming (BM) (PUTMAN & PAULUS, 2009). It is possible to select these criteria according to a dedicated list of criteria, which was developed on the basis of a literature review (Bonilla-Alicea and Fu, 2022; Lagerstedt et al., 2003; Saadé et al., 2022; Varun et al., 2009) and according to the database catalogues for the SimaPro programme, which is one of the most popular programmes for LCA (Various authors, 2020). These criteria are as follows:

1. Carbon footprint (climate change/ greenhouse gas emissions/global warming);
2. Depletion of the ozone layer;
3. Human toxicity (including carcinogenic effects or not);
4. Ecotoxicity (/water);
5. Terrestrial ecotoxicity;
6. Formation of photo-oxidants;
7. Acidification (water/soil);
8. Eutrophication (water/terrestrial);
9. Ozone formation (human health/terrestrial ecosystems);
10. Photochemical oxidant formation potential/photochemical ozone/photochemical oxidation/photochemical ecotoxicity;
11. Waste (hazardous/bulky/radioactive/radioactive/deposited);
12. Abiotic depletion (elements/fossil fuels/other resources);
13. Particulate matter or inorganic substances in the respiratory system/Effects on the respiratory system;
14. Ionising radiation (human health/ecosystems);
15. Land development;
16. Scarcity of resources (mineral/fossil/renewable/aquatic)/Extraction of minerals;
17. Water consumption/water footprint;
18. Heavy metals to water/soil/air;
19. Radioactive substances to air/water;
20. Water pollution;
21. Noise;
22. Soil pesticides;
23. Major air pollutants.

From the developed list of environmental impact criteria for LCA, the team of experts selects only those that may occur for the proposed research subject. According to preliminary research, up to a maximum of nine environmental criteria are most often analysed. On their basis, further analysis is carried out, as presented in the next steps of the model.

Stage 4. Assessment of product criteria in terms of quality and environment

The model assumes that the products will be assessed in terms of quality and environment. This means that all products (selected in stage 1) will be assessed in terms of their satisfaction with use (quality criteria - stage 2) and then in terms of their negative environmental impact in the context of their entire life cycle (LCA) (environmental criteria - stage 3).

The TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) (Chen, 2000; Hameed, Kandasamy, Aravind Raj, Baghdadi, & Shahzad, 2022a) was adopted to assess the products in terms of quality and environment. The choice of this method resulted from its popularity in making decisions based on any criteria (measurable or immeasurable). In addition, the TOPSIS method is an uncomplicated method applicable to the creation of decision rankings, e.g. product alternatives evaluated in terms of various criteria.

It was assumed that the quality and environmental criteria are evaluated separately. As a result, two product selection rankings will be obtained, the first in terms of quality and the second in terms of environment. Therefore, initially, two decision matrices are created, i.e. X_{ij}^{Q} and X_{ij}^{E}, where Q – quality criteria matrix, E – environmental criteria matrix, *i* – products, *j* – criteria, i, *j* = 1, 2, …, *n*. According to the authors of the studies (Siwiec & Pacana, 2021d; Ulewicz, Siwiec, Pacana, Tutak, & Brodny, 2021), it was assumed that the decision matrices take the form (1) as needed:

$$X = [x_{ij}] = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \tag{1}$$

A team of experts uses these matrices to evaluate products against quality and environmental criteria. Ratings are awarded on a Likert scale, where 1 is the low level of quality/or low environmental impact, and 7 is the high level of quality/or high environmental impact.

Then, compute the normalised decision matrices. Their creation is necessary when criteria with different measurement units are analysed (Siwiec & Pacana, 2021c). These matrices are created based on a decision matrix, where, following the authors of articles (Kannan & Thiyagarajan, 2022; Siwiec & Pacana, 2021c), formula (2) is used:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2}$$

Once the normalised decision matrices have been computed, the weighted normalised decision matrices must be computed. To do this, it is necessary to determine the importance of the individual criteria. The validity of product criteria was assumed to be determined by a team of experts, whereas the evaluation of the validity of quality and environmental criteria is determined separately. The weights of the criteria are assigned on a Likert scale, where 1 is a criterion of little importance, and 7 is a very important criterion. Once the criteria weights have been determined, it is possible to develop normalised decision matrices, as shown in formula (3) (Ramón-Canul et al., 2021; 'TOPSIS', 2013)

$$v_{ij} = w_j n_{ij}, where\ i = 1, \ldots, m; j = 1, \ldots, n,$$
$$and\ w_j\ is\ the\ weight\ of\ the\ ith\ attribute\ or\ criterion, and\ \sum_{j=1}^{n} w_j = 1. \tag{3}$$

Then, the ideal positive and ideal negative solutions are determined. These solutions are estimated in a matrix with qualitative criteria and separately in a matrix with environmental criteria. It is assumed that a positive ideal solution (A^+) and a negative ideal solution (A^-) can be determined according to the formulas (4-5) (Siwiec & Pacana, 2021d; Ulewicz et al., 2021):

$$A^+ = (v_1^+, v_2^+, \ldots, v_n^+) = \left(\left(\underset{i}{max} v_{ij} \mid j \in I \right), \left(\underset{i}{min} v_{ij} \mid j \in J \right) \right) \tag{4}$$

$$A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \left(\left(\underset{i}{min} v_{ij} \mid j \in I \right), \left(\underset{i}{max} v_{ij} \mid j \in J \right) \right) \tag{5}$$

where: *I* - applies to benefit criteria, *J* - applies to cost criteria, and *i* = 1, …, *m*; *j* = 1, …, *n*.

A positive ideal solution concerns the maximum results in each of the analysed criteria, which results in the maximisation of benefits and the minimisation of costs. On the other hand, a negative ideal solution means minimum results in each of the analysed criteria, then the costs are maximised, and the benefits are minimised. The function criteria can be benefit functions, that is, more is better, or cost functions, where less is better (Hameed et al., 2022a). Subsequently, it is possible to calculate the separation measures of the positive ideal solution (A^+) and the negative ideal solution (A^-). For this purpose, the n-dimensional Euclidean distance is used, which is expressed as (6-7) (Chen, 2000; Hameed, Kandasamy, Aravind Raj, Baghdadi, & Shahzad, 2022b):

$$A_j^+ = \left\{ \sum_{i=1}^{n} \left(v_{ij} - v_i^+ \right)^2 \right\}^{\frac{1}{2}}, j = 1, \ldots, n \tag{6}$$

$$A_j^- = \left\{\sum_{i=1}^{n}\left(v_{ij} - v_i^-\right)^2\right\}^{\frac{1}{2}}, j = 1, \dots, n \quad (7)$$

In the proposed approach, it is assumed that the selection of the best product is made depending on the quality level of these products, their impact on the natural environment throughout their life cycle (LCA) and taking into account the purchase price of these products. To make this possible, a combination of these three aspects was adopted. This means a combination of the values of a positive and negative ideal solution and then the values of R_j estimated, taking into account the quality criteria of the product with the values of R_j estimated, taking into account the environmental criteria of the product. This is represented by formula (8):

$$A_j^{Q+} + A_j^{E+} = A_j^+ \quad and \quad A_j^{Q-} + A_j^{E-} = A_j^- \quad (8)$$

where: Q - quality criteria, E - environmental criteria, *j* - products, *j* = 1, 2, …, *n*.

As a result, it is possible to compute the relative proximity of a positive ideal solution, which is concerned with determining the relative proximity of the alternative A_i with respect to A^+, as shown by formula (9) (Kannan & Thiyagarajan, 2022; Ramón-Canul et al., 2021):

$$R_j = \frac{d_j^-}{d_j^+ + d_j^-} \quad (9)$$

where: *j* = 1, …, *n*, since $d_j^- \geq 0$ and $d_j^+ \geq 0$, then clearly $R_j \in [0,1]$.

The last step is to organise the results obtained into a qualitative and environmental ranking. The first position in a given ranking is the most advantageous product, i.e. having the best level of quality and having the least negative impact on the natural environment. Based on these rankings, it is possible to make an initial decision on which product is the most preferred in terms of quality and environment. However, to conduct a full analysis, verifying the products in terms of their purchase price is also proposed. This represents the next stage of the model.

Stage 5. Determination of price relationships for the quality and environmental level

At this stage, a modified price-quality analysis is used. The modification of this method consists in implementing the R_j^{QE} indicator, which refers not only to the quality of the product but also to its environmental impact in the context of LCA. In the modified price-quality-environment analysis (ACJ-E), the decision function in general terms is expressed by the formula (10) (Malindzak, 2017; Ulewicz et al., 2021):

$$D = f(C, R_j^{QE}) \quad (10)$$

where: C - purchase price of the product, R_j^{QE} – qualitative-environmental indicator.

On its basis, the calculation of the price-quality ratio (11), the decision interpretation index (12) and the price-quality index (13) are assumed (Ostasz, Siwiec, & Pacana, 2022a; Pacana et al. 2014):

$$e = \frac{p}{q} \quad where: \quad p = \frac{P_a - P}{P_a - P_i} \quad (11)$$

$$d_n = 0{,}5e \qquad for\ unfavourable\ decisions \quad e = (0 \div 1)$$
$$d_k = 0{,}5\left(1 - \frac{1}{e}\right) + 0{,}5 \qquad for\ favourable\ decisions \quad e > 1$$
(12)

$$C_p = \frac{P}{Q} \quad where: \quad Q = R_j^{QE} * 100 \quad (13)$$

where: P – product price, P_a – maximum price among all analysed, P_i – minimum price among all analysed, q – quality and environmental level expressed decimal fraction, e – price-quality ratio.

Then, it is possible to calculate the resolution index for technical preference (14), the resolution index for economic preference (15) and the averaged decision resolution index (16), where the relationships from formula (17) are assumed (Pacana et al., 2014:

$$r_t = 0{,}167(3q + 2d + c) \quad (14)$$

$$r_e = 0{,}167(3c + 2d + q) \quad (15)$$

$$r_d = 0{,}5(r_t + r_e) \quad (16)$$

$$if \quad r_t = \frac{\alpha q + \beta d + \gamma c}{\alpha + \beta + \gamma} \quad or \quad r_e = \frac{\alpha c + \beta d + \gamma q}{\alpha + \beta + \gamma} \quad for \quad c = \frac{C_{Pa} - C_P}{C_{Pa} - C_{Pi}} \quad and \quad \alpha:\beta:\gamma = 3:2:1 \quad (17)$$

The final decision on the best product in terms of quality, environment and purchase price is made based on the r_d index. This represents the next stage of the model.

Stage 6. Choosing the best product

Depending on the needs of the entity (expert), it is possible to make decisions about the choice of product. This is done based on the r_d indicator. On this basis, it is possible to decide which of the analysed products will be both satisfactory in terms of quality level and have the smallest possible impact on the natural environment and a favourable purchase price. The maximum values of r_d indicate the best product. The level of satisfaction with the product can be interpreted according to the scale of relative states (Figure 2).

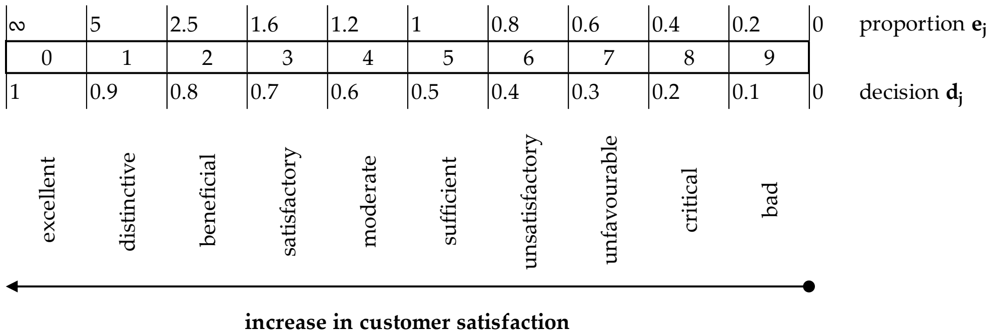

Fig. 2. Scale of states to determine customer satisfaction. Own study based on (Ostasz et al., 2022b; Pacana & Siwiec, 2022b; Siwiec & Pacana, 2021c; Ulewicz et al., 2021).

It is necessary to take into account that the results of the analysis are the result of the assessment of the team of experts. Therefore, as part of other analyses (for instance, other products and criteria), the results obtained should be interpreted individually, depending on the case selected for analysis.

Results

The model test was carried out as part of the selection of a mining excavator for Kruszgeo S.A. located in Poland. It is a company that produces aggregate and provides geological services. It is one of the largest companies in this industry, having its plants in the Podkarpackie and Lesser Poland territories. In the company, it is important to carry out mining processes effectively. Therefore, it is important to properly modernise the services provided to simultaneously care for their quality, considering their impact on the natural environment and economic aspects. Therefore, it was considered reasonable to use the proposed model (taking into account quality, environmental, and cost aspects at the same time) for the selection of a mining excavator. The test result is presented in six main stages.

Stage 1. Selection of products and determination of the research goal

Initially, the expert (subject) selected the products for analysis. Due to the individual preferences of the entity, it was decided to analyse CATERPILLAR-type mini excavators from CAT, which is a leader in the manufacture of these products. There were eight CATERPILLAR mini excavators, i.e., 303.5, 302 CR, 301.8, 300.9 D, 301.5, 301.7 CR, 304 and 301.8. These excavators were randomly and conventionally named E1-E8.

The purpose of the research was then defined. The goal was determined by the entity (an expert) according to the SMARTER method. In the proposed approach, the aim was to select an excavator that would be the most advantageous in terms of quality (efficient and effective), at the same time, would have a minimal negative impact on the natural environment throughout its life cycle (LCA), and would also be beneficial in terms of the purchase cost.

Stage 2. Identifying and characterising product quality criteria

All mini excavators selected for analysis were characterised in terms of the criteria of these products. The criteria were selected by an expert (entity). It was based on publicly available catalogues of these excavators. Due to the large number of criteria characterising excavators, only those that have the greatest impact on their performance have been selected. For the purposes of the analysis, these criteria were as follows:

- C1 - useful engine power (kW), i.e. engine power, which is measured on driven wheels,
- C2 - cylinder diameter (mm), so the diameter of the element of the mechanical structure inside which the piston moves,
- C3 - cubic capacity (l), i.e. the difference between the maximum and minimum cylinder volume,
- C4 - maximum power (kW), which is the power value that can be achieved under optimal conditions,
- C5 - operating weight (kg), which is the maximum weight that is carried for a given range of motion,
- C6 - digging depth (mm), i.e. the maximum depth to which the excavation can be made,
- C7 - belt width (mm), i.e. the width of the lane used for the passage of the excavator,
- C8 - maximum reach (mm), i.e. the maximum working range,
- C9 - arm length (mm), i.e. reach length of the excavator's arm only.

The characteristics of the excavators in terms of these criteria are presented in Table 1.

Tab. 1. Characteristics of CATERPILLAR mini excavators according to selected quality criteria

	useful engine power [kW]	cylinder diameter [mm]	cubic capacity [l]	maximum power [kW]	operating weight [kg]	digging depth [mm]	belt/shoe width [mm]	maximum reach [mm]	arm length [mm]
	C1	C2	C3	C4	C5	C6	C7	C8	C9
P1	17.6	84	1.7	18.4	4190	3110	300	5510	1560
P2	15.7	77	1.1	16.1	2262	2570	250	4270	960
P3	15.7	77	1.1	16.1	2029	2570	230	3870	1160
P4	9.6	73	0.854	13.7	953	1731	180	3074	890
P5	15.7	71	1.1	16.1	1775	2540	230	3800	960
P6	15.7	77	1.1	16.1	1915	3490	230	3800	960
P7	33.6	84	1.662	33.6	4475	3210	350	5330	1395
P8	15.7	77	1.1	17.5	2029	2570	230	4030	1160

Based on these criteria, the quality of excavators was analysed in the following part of the analysis. According to these criteria, the quality level of the excavators was determined. This is presented in the next part of the analysis.

Stage 3. Identify environmental criteria in the context of LCA

In order to analyse the impact of excavators on the natural environment throughout their life cycle (LCA), a simplified verification was adopted. This involved performing a life-cycle assessment of the excavators without taking into account quantitative interpretations of environmental impacts, where these assessments are based on the knowledge and opinion of a team of experts. Therefore, a team of experts evaluated the negative impact of excavators on the environment, taking into account the key environmental criteria that occur at various life cycle stages (LCA). The selection of these criteria was made based on the developed list of environmental criteria within the LCA (as presented in the general description of the model). These criteria were as follows:

- Climate change (CE1),
- Acidification (water/soil) (CE2),
- Global warming (CE3),
- Waste (hazardous/bulky/radioactive/radioactive/deposited) (CE4),
- Abiotic depletion (elements/fossil fuels/other resources) (CE5),
- Land use (CE6),
- Noise (CE7),
- Heavy metals to water/soil/air (CE8).

Based on these environmental criteria, further analysis is performed, as shown in the next steps of the model.

Stage 4. Assessment of product criteria in terms of quality and environment

At this stage, a team of experts assessed the excavators in terms of quality and environment. This involved the evaluation of all excavators (selected in Step 1) on the basis of quality criteria (selected in Step 2) and environmental criteria (selected in Step 3). Qualitative and environmental criteria were assessed and analysed separately using the TOPSIS method. Therefore, according to the formula (1), two decision matrices were created, i.e.: X_{ij}^{Q} and X_{ij}^{E}, where Q – matrix of quality criteria, E – matrix of environmental criteria, i – products, j – criteria, $i, j = 1, 2, \ldots, n$. They are presented in Table 2 and Table 3.

Tab. 2. Evaluation of quality criteria for eight CATERPILLAR mini excavators

	useful engine power [kW]	cylinder diameter [mm]	cubic capacity [l]	maximum power [kW]	operating weight [kg]	digging depth [mm]	belt/shoe width [mm]	maximum reach [mm]	arm length [mm]
	CQ1	CQ2	CQ3	CQ4	CQ5	CQ6	CQ7	CQ8	CQ9
P1	5	7	7	5	7	7	6	7	7
P2	4	6	5	3	6	6	5	6	4
P3	4	6	5	3	5	6	5	5	5
P4	3	5	3	2	3	4	4	4	3
P5	4	4	5	3	4	5	5	5	4
P6	4	6	5	3	4	7	5	5	4
P7	7	7	7	7	7	7	7	7	6
P8	4	6	5	4	5	6	5	6	5

Tab. 3. Evaluation of environmental criteria according to LCA for eight CATERPILLAR mini excavators

	climate change	acidification (water/soil)	global warming	waste	abiotic depletion	land use	noise	heavy metals to water/soil/air
	CE1	CE2	CE3	CE4	CE5	CE6	CE7	CE8
P1	5	4	2	5	5	5	4	5
P2	4	3	2	5	4	4	3	4
P3	4	3	2	5	4	4	3	3
P4	3	2	2	3	2	3	2	2
P5	4	2	2	5	3	4	3	3
P6	4	3	2	5	3	4	3	3
P7	3	4	2	6	5	5	2	5
P8	4	3	2	4	4	4	3	4

Ratings were given on a Likert scale, where 1 is a low level of quality / low impact on the environment, and 7 is a high level of quality / high impact on the environment. Subsequently, normalised decision matrices were computed. Formula (2) was used for this. These matrices are presented in Tables 4 and 5.

Tab. 4. Standardised decision matrices for quality criteria for eight CATERPILLAR mini excavators

	useful engine power [kW]	cylinder diameter [mm]	cubic capacity [l]	maximum power [kW]	operating weight [kg]	digging depth [mm]	belt/shoe width [mm]	maximum reach [mm]	arm length [mm]
	CQ1	CQ2	CQ3	CQ4	CQ5	CQ6	CQ7	CQ8	CQ9
P1	0.39	0.42	0.46	0.44	0.47	0.41	0.40	0.43	0.51
P2	0.31	0.36	0.33	0.26	0.40	0.35	0.33	0.37	0.29
P3	0.31	0.36	0.33	0.26	0.33	0.35	0.33	0.31	0.36
P4	0.23	0.30	0.20	0.18	0.20	0.23	0.27	0.25	0.22
P5	0.31	0.24	0.33	0.26	0.27	0.29	0.33	0.31	0.29
P6	0.31	0.36	0.33	0.26	0.27	0.41	0.33	0.31	0.29
P7	0.55	0.42	0.46	0.61	0.47	0.41	0.47	0.43	0.43
P8	0.31	0.36	0.33	0.35	0.33	0.35	0.33	0.37	0.36

Tab. 5. Standardised decision matrices for LCA environmental criteria for eight CATERPILLAR mini excavators

	climate change CE1	acidification (water/soil) CE2	global warming CE3	waste CE4	abiotic depletion CE5	land use CE6	noise CE7	heavy metals to water/soil/air CE8
P1	0.45	0.46	0.35	0.37	0.46	0.42	0.48	0.47
P2	0.36	0.34	0.35	0.37	0.37	0.34	0.36	0.38
P3	0.36	0.34	0.35	0.37	0.37	0.34	0.36	0.28
P4	0.27	0.23	0.35	0.22	0.18	0.25	0.24	0.19
P5	0.36	0.23	0.35	0.37	0.27	0.34	0.36	0.28
P6	0.36	0.34	0.35	0.37	0.27	0.34	0.36	0.28
P7	0.27	0.46	0.35	0.44	0.46	0.42	0.24	0.47
P8	0.36	0.34	0.35	0.29	0.37	0.34	0.36	0.38

Later, formulas (3-5) were used to calculate weighted normalised decision matrices. To do this, a team of experts assessed the validity of qualitative and environmental criteria. He used a scale from 1 to 7 for this. Eventually, positive- and negative-ideal solutions were defined. It has been assumed that all qualitative criteria are benefit criteria (the more, the better). However, all environmental criteria are cost criteria (the more, the worse). The result is shown in Tables 6 and 7.

Tab. 6. Weighted standardised decision matrices for quality criteria for eight CATERPILLAR mini excavators

	useful engine power [kW] CQ1	cylinder diameter [mm] CQ2	cubic capacity [l] CQ3	maximum power [kW] CQ4	operating weight [kg] CQ5	digging depth [mm] CQ6	belt/shoe width [mm] CQ7	maximum reach [mm] CQ8	arm length [mm] CQ9
W	0.7	0.7	0.5	0.6	0.6	0.5	0.4	0.4	0.3
P1	0.27	0.29	0.23	0.26	0.28	0.20	0.16	0.17	0.15
P2	0.22	0.25	0.16	0.16	0.24	0.17	0.13	0.15	0.09
P3	0.22	0.25	0.16	0.16	0.20	0.17	0.13	0.12	0.11
P4	0.16	0.21	0.10	0.11	0.12	0.12	0.11	0.10	0.06
P5	0.22	0.17	0.16	0.16	0.16	0.15	0.13	0.12	0.09
P6	0.22	0.25	0.16	0.16	0.16	0.20	0.13	0.12	0.09
P7	0.38	0.29	0.23	0.37	0.28	0.20	0.19	0.17	0.13
P8	0.22	0.25	0.16	0.21	0.20	0.17	0.13	0.15	0.11
Max	0.38	0.29	0.23	0.37	0.28	0.20	0.19	0.17	0.15
Min	0.16	0.17	0.10	0.11	0.12	0.12	0.11	0.10	0.06

Tab. 7. Weighted normalised decision matrices for LCA environmental criteria for eight CATERPILLAR mini excavators

	climate change CE1	acidification (water/soil) CE2	global warming CE3	waste CE4	abiotic depletion CE5	land use CE6	noise CE7	heavy metals to water/soil/air CE8
W	0.7	0.4	0.5	0.6	0.5	0.2	0.3	0.4
P1	0.32	0.18	0.18	0.22	0.23	0.08	0.14	0.19
P2	0.25	0.14	0.18	0.22	0.18	0.07	0.11	0.15
P3	0.25	0.14	0.18	0.22	0.18	0.07	0.11	0.11
P4	0.19	0.09	0.18	0.13	0.09	0.05	0.07	0.08
P5	0.25	0.09	0.18	0.22	0.14	0.07	0.11	0.11
P6	0.25	0.14	0.18	0.22	0.14	0.07	0.11	0.11
P7	0.19	0.18	0.18	0.26	0.23	0.08	0.07	0.19
P8	0.25	0.14	0.18	0.18	0.18	0.07	0.11	0.15
Max	0.19	0.09	0.18	0.13	0.09	0.05	0.07	0.08
Min	0.32	0.18	0.18	0.26	0.23	0.08	0.14	0.19

Later, formulas (6-8) were used to calculate the separation measures from the positive ideal solution (A^{+}) and the negative ideal solution (A^{-}), and also to calculate the relative proximity of the positive ideal solution, which is concerned with determining the relative proximity of the alternative A_i with respect to A^{+}. In the proposed approach, it is assumed that the selection of the best product is based on the quality level of these products, their impact on the natural environment throughout their life cycle (LCA), and considering the purchase price of these products. For this purpose, the results obtained in Step 4 were combined. For this purpose, formula (9) was used, where the result is presented in Table 8.

Tab. 8. TOPSIS score for excavators according to the quality and environmental index

	Quality		Environment		Quality and environmental indicator			
	A^{+}	A^{-}	A^{+}	A^{-}	A^{+}	A^{-}	R_j	Ranking
P1	0.15	0.34	0.26	0.04	0.42	0.39	0.48	2
P2	0.30	0.20	0.17	0.11	0.47	0.31	0.40	6
P3	0.30	0.17	0.16	0.13	0.46	0.30	0.40	6
P4	0.44	0.04	0.00	0.28	0.44	0.32	0.42	4
P5	0.34	0.12	0.13	0.17	0.47	0.29	0.38	7
P6	0.32	0.17	0.14	0.15	0.46	0.32	0.41	5
P7	0.02	0.45	0.24	0.15	0.26	0.59	0.69	1
P8	0.27	0.20	0.15	0.14	0.42	0.34	0.45	3

Based on the obtained R_j values, quality and environmental ranking were created. It was shown that the most favourable in terms of quality is the P7 excavator, followed by P1, P8, and P4. On the other hand, the P5 excavator turned out to be the least favourable. To take into account the purchase price of these excavators, a modified price-quality-environmental analysis was carried out, as presented in the next stage of the model.

Stage 5. Determination of price relationships for the quality and environmental level

As part of this stage, the results were verified using the modified price-quality-environmental analysis (ACJ-E). The purchase prices of the mini excavators were established on the basis of the generally available sales prices of these products. Prices are expressed in euros (€). According to formulas (10-13), the price-quality ratio, the decision interpretation index, and the price index were calculated. Subsequently, using the formulas (14-17), the determination index for technical, economic, and decision-making preference was calculated. The result of the modified price-quality-environmental analysis (ACJ-E) is presented in Table 9.

Tab. 9. TOPSIS score for excavators according to the quality and environmental index

Product	P1	P2	P3	P4	P5	P6	P7	P8
$Q = R_j^{QE}*100$	48.14	39.92	39.78	42.36	38.18	41.32	69.20	44.62
$q = R_j^{QE}$	0.48	0.40	0.40	0.42	0.38	0.41	0.69	0.45
P	224200	162000	147400	73677	36500	103000	174549	154899
p	0.00	0.33	0.41	0.80	1.00	0.65	0.26	0.37
e	0.00	0.83	1.03	1.89	2.62	1.56	0.38	0.83
d_k	0.00	0.42	0.51	0.74	0.81	0.68	0.19	0.41
C_p	4657.62	4058.09	3705.56	1739.16	956.11	2492.65	2522.31	3471.40
c	0.00	0.16	0.26	0.79	1.00	0.58	0.58	0.32
r_t	0.24	0.37	0.41	0.59	0.63	0.53	0.51	0.42
r_e	0.08	0.29	0.37	0.71	0.84	0.59	0.47	0.37
r_d	0.16	0.33	0.39	0.65	0.73	0.56	0.49	0.39

The final decision on the best product in terms of quality, environment and purchase price is made on the basis of the r_d index. This is presented in the next part of the article.

Stage 6. Choosing the best product

Based on the decision resolution index (r_d), a decision was made on the most advantageous CATERPILLAR mini excavator. This decision concerns the excavator, which turned out to be the most advantageous in terms of quality, environment, and price. The scale of relative states was used to analyse the r_d index and determine the quality, environmental, and price levels. The analysis of the results obtained is presented in Table 10.

Tab. 10. ACJ-E score for excavators according to the quality-price-environment index

Product	P1	P2	P3	P4	P5	P6	P7	P8
r_d	0.16	0.33	0.39	0.65	0.73	0.56	0.49	0.39
Decision	Critical	unsatisfactory	unsatisfactory	Satisfactory	Beneficial	Moderate	Sufficient	unsatisfactory
Ranking	7	6	5	2	1	3	4	5

It was concluded that the conventionally marked mini-excavator P5 is the most suitable. According to the team of experts, it is an excavator that will meet the expectations of the entity (expert) in the best way. According to the team of experts, the P5 excavator is satisfied at the same time in terms of quality level, has the lowest possible environmental impact over the entire life cycle, and has a relatively favourable purchase price. Next, it is a good idea to pay attention to the P5 or P6 excavator. The worst result was obtained by the excavator marked as P1. However, the results of the analysis are the result of the expert team's assessment and the entity's individual needs. Therefore, under other analyses, the result may be different.

Discussion

The environmental impact, but also the quality level, is considered a determinant of well-functioning organisations that care at the same time about the level of customer satisfaction but also about the natural environment (Siwiec & Pacana, 2021d, 2021b, 2021a). In the context of sustainable development, it is also good to consider economic aspects (Gajdzik, Wolniak, & Grebski, 2022; Gawlik, Krajewska-Śpiewak, & Zębala, 2016; Grabowski, Gawlik, Krajewska-Śpiewak, Skoczypiec, & Tyczyński, 2022; Lazar, Potočan, Klimecka-Tatar, & Obrecht, 2022). Combining qualitative, environmental, and economic criteria at the same time is difficult, especially in the mining industry. This is also due to the fact that environmental aspects should be analysed throughout the entire life cycle. Therefore, the objective was to develop a simplified model that supports decision making, taking into account the criteria of sustainable development and life cycle assessment (LCA). The model was tested on the example of CATERPILLAR mini excavators. The conducted analysis was extended by comparing the obtained indicators, i.e. quality-environmental (R_j^{QE}) and quality-environmental-price (r_d). These indicators were described according to the scale of relative states, and for these results, the place in the ranking of the excavator was indicated. This is presented in Table 11.

Tab. 11. Comparison of indicators from the proposed model

Product	P1	P2	P3	P4	P5	P6	P7	P8
R_j^{QE}	0.48	0.40	0.40	0.42	0.38	0.41	0.69	0.45
Decision	Sufficient	unsatisfactory	unsatisfactory	Sufficient	unsatisfactory	Sufficient	Satisfactory	Sufficient
Ranking	2	5	5	3	6	4	1	3
r_d	0.16	0.33	0.39	0.65	0.73	0.56	0.49	0.39
Decision	Critical	unsatisfactory	unsatisfactory	Satisfactory	Beneficial	Moderate	Sufficient	unsatisfactory
Ranking	7	6	5	2	1	3	4	5

Taking into account the level of quality of the excavators and their impact on the natural environment, it was shown that the most advantageous excavator is P7 (R_j^{QE} = 0.69). After taking into account the purchase price, the P7 excavator took fourth place with the index value r_d = 0.49. Significant differences were observed in the case of the P1 excavator, which took second place in the quality and environmental ranking. However, after taking into account the price, it took the last (seventh) place. Similar results were obtained for the P5 excavator, which was ranked first in the final ranking (quality-environment-price). It was proposed that the P5 excavator be chosen as the most advantageous in terms of these three aspects. However, in the quality and environmental ranking, it was in the last place. For this reason, it was observed that, in this case, the price significantly impacted the final ranking of the products. However, the results obtained result from the individual preferences of the entity using the proposed model. Therefore, depending on the needs, the results obtained using the model may be different.

The benefits of the proposed model include:

- the ability to support the decision to choose a product based on three aspects: quality, environmental (impact on the natural environment throughout the life cycle) and price (actual purchase price),
- streamlining the process of making decisions about the best product,
- improving the organisation's operations in accordance with the principles of sustainable development,

- protection of the natural environment by paying attention to the usefulness of the product throughout its life cycle,
- the possibility of increasing customer satisfaction with the services offered,
- The possibility of reducing the cost of purchasing products.

However, the disadvantage of the proposed model is the ability to analyse a relatively small number of products and their corresponding criteria. Additionally, the model is dedicated to supporting individual entities because the results obtained depend on the preferences of this entity and its purchasing capabilities. Therefore, it is impossible to compare the results of the model with the results obtained, for example, for a different type of product. Another disadvantage of the model is the lack of taking into account the real values of environmental impacts in the LCA. However, the model turned out to be useful in making decisions for an individual entity.

Therefore, future research will consist of analysing the sensitivity of the obtained results when changing various values of qualitative, environmental, and purchase price indicators. In addition, it is planned to extend the model with the use of appropriate LCA software.

Conclusions

Making favourable decisions according to sustainable development criteria is a key action to improve the natural environment. It is also an important area to meet the expectations of society. However, managing these aspects simultaneously remains difficult. The objective of the article was to develop a simplified model supporting decision-making, taking into account the criteria of sustainable development and life cycle assessment (LCA).

The methodology consisted of the use of the TOPSIS method and the modified price-quality analysis considering the environmental aspect (ACJ-E), which were combined. The model was tested on the example of eight CATERPILLAR mini excavators, which were selected for the Kruszgeo S.A. mining and service company located in Poland. All the excavators analysed were analysed according to quality criteria and environmental criteria related to the life cycle of these products. The qualitative criteria selected for this analysis were: engine power, cylinder diameter, displacement, maximum power, operating weight, digging depth, track/track width, maximum reach, and arm length. However, the life cycle (LCA) environmental criteria analysed were: climate change, acidification (water/soil), global warming, waste, abiotic depletion (elements/fossil fuels/other resources), land use, noise, and heavy metals to water/soil/air. Using the TOPSIS method, excavators were analysed according to quality criteria and then according to environmental criteria. The indicators obtained were combined into a qualitative environmental indicator. Then, the obtained quality-environmental indicator was combined with the purchase price. A modified ACJ-E was used for this. Finally, according to the scale of relative states, a ranking of products (excavators) was created. It was concluded that the most suitable mini excavator, conventionally marked P5, is satisfactory in terms of quality, has the lowest possible environmental impact throughout its life cycle, and has a relatively favourable purchase price.

The test study was conducted on the example of CATERPILLAR mini excavators. However, the model can be dedicated to all companies that want to make decisions in accordance with the idea of sustainable development.

References

Adiansyah, J. S., Rosano, M., Vink, S., & Keir, G. (2015). A framework for a sustainable approach to mine tailings management: disposal strategies. *Journal of Cleaner Production*, 108, 1050–1062. https://doi.org/10.1016/j.jclepro.2015.07.139

Ahmad, M., Ahmed, Z., Gavurova, B., & Oláh, J. (2022). Financial risk, renewable energy technology budgets, and environmental sustainability: Is going green possible? *Frontiers in Environmental Science*, 10, 909190. https://doi.org/10.3389/fenvs.2022.909190

Androniceanu, A. (2023). The new trends of digital transformation and artificial intelligence in public administration. *Administratie si Management Public*, 40, 147-155. https://doi.org/10.24818/amp/2023.40-09

Awuah-Offei, K., & Adekpedjou, A. (2011). Application of life cycle assessment in the mining industry. *The International Journal of Life Cycle Assessment*, 16(1), 82–89. https://doi.org/10.1007/s11367-010-0246-6

Bednárová L, Pavolová H, Šimková Z, & Bakalár T. (2023). Economic Efficiency of Solar and Rainwater Systems—A Case Study. *Energies*, 16(1), 504. https://doi.org/10.3390/en16010504

Belas, J., Strnad, Z., Gavurova, B., & Čepel, M. (2019). Business environment quality factors research-SME management's platform. *Polish journal of management studies*, 20(1), 64-77. https://doi.org/10.17512/pjms.2019.20.1.06

Blengini, G. A., Garbarino, E., Šolar, S., Shields, D. J., Hámor, T., Vinai, R., & Agioutantis, Z. (2012). Life Cycle Assessment guidelines for the sustainable production and recycling of aggregates: the Sustainable Aggregates

Resource Management project (SARMa). *Journal of Cleaner Production*, 27, 177–181. Retrieved from https://doi.org/10.1016/j.jclepro.2012.01.020

Bogusz, K., & Sulich, A. (2020). The Sustainable Development Strategies in Mining Industry. *Education Excellence and Innovation Management through Vision*, 1(1), 6893–6911.

Bogusz, M., Matysik-Pejas, R., Krasnodębski, A., & Dziekański, P. (2021). The Concept of Zero Waste in the Context of Supporting Environmental Protection by Consumers. *Energies*, 14(18), 5964. https://doi.org/10.3390/en14185964

Bonilla-Alicea, R. J., & Fu, K. (2022). Social life-cycle assessment (S-LCA) of residential rooftop solar panels using challenge-derived framework. *Energy, Sustainability and Society*, 12(1), 7. https://doi.org/10.1186/s13705-022-00332-w

Burchart-Korol, D., Fugiel, A., Czaplicka-Kolarz, K., & Turek, M. (2016). Model of environmental life cycle assessment for coal mining operations. *Science of The Total Environment*, 562, 61–72. https://doi.org/10.1016/j.scitotenv.2016.03.202

Calado, E. A., Leite, M., & Silva, A. (2019). Integrating life cycle assessment (LCA) and life cycle costing (LCC) in the early phases of aircraft structural design: an elevator case study. *The International Journal of Life Cycle Assessment*, 24(12), 2091–2110. https://doi.org/10.1007/s11367-019-01632-8

Capony, A., Lorino, T., Muresan, B., Baudru, Y., Dauvergne, M., Dunand, M., … Jullien, A. (2012). Assessing the Productivity and the Environmental Impacts of Earthwork Machines: A Case Study for GPS-Instrumented Excavator. *Procedia - Social and Behavioral Sciences*, 48, 256–265. https://doi.org/10.1016/j.sbspro.2012.06.1006

Chen, C.-T. (2000). Extensions of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets and Systems*, 114(1), 1–9. https://doi.org/10.1016/S0165-0114(97)00377-1

Damigos, D. (2006). An overview of environmental valuation methods for the mining industry. *Journal of Cleaner Production*, 14(3–4), 234–247. https://doi.org/10.1016/j.jclepro.2004.06.005

Dolinayova, A., & Domeny, I. (2022). Competition on the Railway Market in a Segment of Public Service Obligations in Terms of Effectiveness: Study in V4 Countries. *Journal of Competitiveness*, 14(3), 41–58. https://doi.org/10.7441/joc.2022.03.03

Durocher, D. B., & Putnam, R. (2013). Mining industry process upgrades to reduce energy intensity while improving end product quality. In *2013 Workshop on Power Electronics and Power Quality Applications (PEPQA)* (pp. 1–7). IEEE. https://doi.org/10.1109/PEPQA.2013.6614964

Fulajtárová, M., & Gavura, Š. (2022). Evaluation and solutions for near misses in the industry. In: International Science Conference Strategies and Innovations in the Raw Materials Policy of the Slovak Republic and the EU - historical development of the importance of raw materials: Conference Proceeding, 7.-9. september 2022, Banská Štiavnica. - Košice (Slovensko): Technická univerzita v Košiciach s. 208-214. ISBN 978-80-553-4187-3

Gajdzik, B., Wolniak, R., & Grebski, W. W. (2022). An Econometric Model of the Operation of the Steel Industry in POLAND in the Context of Process Heat and Energy Consumption. *Energies*, 15(21), 7909. https://doi.org/10.3390/en15217909

Gawlik, J., Krajewska-Śpiewak, J., & Zębala, W. (2016). Identification of the Minimal Thickness of Cutting Layer Based on the Acoustic Emission Signal. *Key Engineering Materials*, 686, 39–44. https://doi.org/10.4028/www.scientific.net/KEM.686.39

Gavurova, B., Privara, A., Janikova, J., & Kovac, V. (2021). Quantification of Tourism Sector Parameters Related to Competitiveness of Countries According to Macroeconomic Indicators. *Journal of Competitiveness*, 13(3), 56–72. https://doi.org/10.7441/joc.2021.03.04

Gavurova, B., Schonfeld, J., Bilan, Y., & Dudas, T. (2022). Study of the Differences in the Perception of the Use of the Principles of Corporate Social Responsibility in Micro, Small and Medium-Sized Enterprises in the V4 Countries. *Journal of Competitiveness*, 14(2), 23–40. https://doi.org/10.7441/joc.2022.02.02

Grabowski, M., Gawlik, J., Krajewska-Śpiewak, J., Skoczypiec, S., & Tyczyński, P. (2022). Technological Possibilities of the Carbide Tools Application for Precision Machining of WCLV Hardened Steel. *Advances in Science and Technology Research Journal*, 16(1), 141–148. https://doi.org/10.12913/22998624/144340

Hameed, A. Z., Kandasamy, J., Aravind Raj, S., Baghdadi, M. A., & Shahzad, M. A. (2022a). Sustainable Product Development Using FMEA ECQFD TRIZ and Fuzzy TOPSIS. *Sustainability*, 14(21), 14345. https://doi.org/10.3390/su142114345

Hameed, A. Z., Kandasamy, J., Aravind Raj, S., Baghdadi, M. A., & Shahzad, M. A. (2022b). Sustainable Product Development Using FMEA ECQFD TRIZ and Fuzzy TOPSIS. *Sustainability*, 14(21), 14345. https://doi.org/10.3390/su142114345

Hilson, G., & Murck, B. (2000). Sustainable development in the mining industry: clarifying the corporate perspective. *Resources Policy*, 26(4), 227–238. Retrieved from https://doi.org/10.1016/S0301-4207(00)00041-6

Chapčáková, A., Hečková, J., Gombár, M., Gavura, Š., Ratnayake Kaščáková, D. (2022). An analysis of the impact of selected predictors for cross-border M&A activity within the European area. Entrepreneurship and Sustainability Issues, 10(2), 176-188. http://dx.doi.org/10.9770/jesi.2022.10.2(11)

Kannan, D., & Thiyagarajan, R. (2022). Entropy based <scp>TOPSIS</scp> method for controller selection in software defined networking. *Concurrency and Computation: Practice and Experience*, 34(1). Retrieved from https://doi.org/10.1002/cpe.6499

Karas, M. (2022). The Hazard Model for European SMEs: Combining Accounting and Macroeconomic Variables. *Journal of Competitiveness*, 14(3), 76–92. https://doi.org/10.7441/joc.2022.03.05

Khalilsanjani, A., Saparauskas, J., Yazdani-Chamzini, A., Turskis, Z., & Feyzbakhsh, A. (2021). Developing a Model Based on Sustainable Development for Prioritizing Entrepreneurial Challenges Under a Competitive Environment. *Journal of Competitiveness*, 13(3), 73–91. https://doi.org/10.7441/joc.2021.03.05

Kravcakova Vozarova, I., Kosikova, M., Heckova, J., Chapcakova, A., & Fulajtarova, M. (2022). The impact of GDP on M&A volume in the European area in the context of the consolidation of the banking market. *Entrepreneurship and Sustainability Issues*, 10(2), 207-216. http://doi.org/10.9770/jesi.2022.10.2(13)

Kristóf, T. & Virág, M. (2022). What drives financial competitiveness of industrial sectors in Visegrad Four countries? Evidence by use of machine learning techniques. *Journal of Competitiveness*, 14(4), 117–136. https://doi.org/10.7441/joc.2022.04.07

Lagerstedt, J., Luttropp, C., & Lindfors, L.-G. (2003). Functional priorities in LCA and design for environment. *The International Journal of Life Cycle Assessment*, 8(3), 160–166. https://doi.org/10.1007/BF02978463

Lawor, B., & Hornyak, M. (2012). Smart goals: how the application of smart goals can contribute to achievement of student learning outcomes. *Developments in Business Simulation and Experiential Learning*, 39, 259–267.

Lazar, S., Potočan, V., Klimecka-Tatar, D., & Obrecht, M. (2022). Boosting Sustainable Operations with Sustainable Supply Chain Modeling: A Case of Organizational Culture and Normative Commitment. *International Journal of Environmental Research and Public Health*, 19(17), 11131. https://doi.org/10.3390/ijerph191711131

Malindzak, D; Pacana, A.; Pacaiova, H. (2017). An effective model for the quality of logistics and improvement of environmental protection in a cement plant. *Przemysł Chemiczny*, 96(9), 1958–11962, doi: 10.15199/62.2017.9.31

Nicolas, C., Rojas-Mora, J., & Valenzuela-Fernández, L. (2020). Causal relationships between economic activity and the mining industry in Chile. *Journal of Intelligent & Fuzzy Systems*, 38(5), 5405–5412. https://doi.org/10.3233/JIFS-179633

Ostasz, G., Siwiec, D., & Pacana, A. (2022a). Model to Determine the Best Modifications of Products with Consideration Customers' Expectations. *Energies*, 15(21), 8102. https://doi.org/10.3390/en15218102

Ostasz, G., Siwiec, D., & Pacana, A. (2022b). Universal Model to Predict Expected Direction of Products Quality Improvement. *Energies*, 15(5). https://doi.org/10.3390/en15051751

Pacana, A. & Siwiec, D. (2021). Universal Model to Support the Quality Improvement of Industrial Products. *Materials*, 14, 7872. https://doi:10.3390/ma14247872

Pacana, A. & Siwiec, D. (2022a). Method of Determining Sequence Actions of Products Improvement. *Materials*, 15(18), 6321. https://doi.org/10.3390/ma15186321

Pacana, A., & Siwiec, D. (2022b). Model to Predict Quality of Photovoltaic Panels Considering Customers' Expectations. *Energies*, 15(3), 1101. https://doi.org/10.3390/en15031101

Pacana, A., Bednarova, L., Pacana, J., Liberko, I., Woźny, A., Malindzak D. (2014). Effect of selected factors of the production process of stretch film for its resistance to puncture. Przemysl Chemiczny 2014, 93(12), 2263–2264

Putman, V. L., & Paulus, P. B. (2009). Brainstorming, Brainstorming Rules and Decision Making. *The Journal of Creative Behavior*, 43(1), 29–40. https://doi.org/10.1002/j.2162-6057.2009.tb01304.x

Ramón-Canul, L. G., Margarito-Carrizal, D. L., Limón-Rivera, R., Morales-Carrrera, U. A., Rodríguez-Buenfil, I. M., Ramírez-Sucre, M. O., Cabal-Prieto, A, Herrera-Corredor, J. A., & Ramírez-Rivera, E. (2021). Technique for order of preference by similarity to ideal solution TOPSIS method for the generation of external preference mapping using rapid sensometric techniques. *Journal of the Science of Food and Agriculture*, 101(8), 3298–3307. https://doi.org/10.1002/jsfa.10959

Rybárová J., Gabániová Ľ., Bednárová L., Rybár R., & Beer M. (2022). Strengthening the Mitigation of Climate Change Impacts in Slovakia through the Disaggregation of Cultural Landscapes. *Processes*, 10(4):658. https://doi.org/10.3390/pr10040658

Saadé, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., & Roux, C. (2022). Combining circular and LCA indicators for the early design of urban projects. *The International Journal of Life Cycle Assessment*, 27(1), 1–19. https://doi.org/10.1007/s11367-021-02007-8

Saaty, T. L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research*, 145(1), 85–91. https://doi.org/10.1016/S0377-2217(02)00227-8

Saaty, T. L., & Tran, L. T. (2007). On the invalidity of fuzzifying numerical judgments in the Analytic Hierarchy Process. *Mathematical and Computer Modelling*, 46(7–8), 962–975. https://doi.org/10.1016/j.mcm.2007.03.022

Siwiec, D., & Pacana, A. (2021a). A Pro-Environmental Method of Sample Size Determination to Predict the Quality Level of Products Considering Current Customers' Expectations. *Sustainability*, 13(10), 5542. https://doi.org/10.3390/su13105542

Siwiec, D., & Pacana, A. (2021b). Method of improve the level of product quality. *Production Engineering Archives*, 27(1), 1–7. https://doi.org/10.30657/pea.2021.27.1

Siwiec, D., & Pacana, A. (2021c). Model of Choice Photovoltaic Panels Considering Customers' Expectations. *Energies*, 14(18), 5977. https://doi.org/10.3390/en14185977

Siwiec, D., & Pacana, A. (2021d). Model Supporting Development Decisions by Considering Qualitative–Environmental Aspects. *Sustainability*, 13(16), 9067. https://doi.org/10.3390/su13169067

Siwiec, D., & Pacana, A. (2022). A New Model Supporting Stability Quality of Materials and Industrial Products. *Materials*, 15(13), 4440. https://doi.org/10.3390/ma15134440

Siwiec, D., Pacana, J., & Pacana, A. (2023). A Novelty Procedure to Identify Critical Causes of Materials Incompatibility. *Materials*, 16(10), 3884. https://doi.org/10.3390/ma16103884

Suppen, N., Carranza, M., Huerta, M., & Hernández, M. A. (2006). Environmental management and life cycle approaches in the Mexican mining industry. *Journal of Cleaner Production*, 14(12–13), 1101–1115. https://doi.org/10.1016/j.jclepro.2004.12.020

Tej, J., Taha, V.A., Bednárová, L., & Sirková, M. (2014). Management simulation exercises — Insight into their use in the educational process. IEEE 12th IEEE International Conference on Emerging eLearning Technologies and Applications (ICETA), Stary Smokovec, Slovakia, 2014,. 29-34. https://doi.org/10.1109/ICETA.2014.7107544

TOPSIS. (2013). In *Multi-Criteria Decision Analysis* (pp. 213–221). Chichester, UK: John Wiley & Sons Ltd. https://doi.org/10.1002/9781118644898.ch8

Ulewicz, R., Siwiec, D., Pacana, A., Tutak, M., & Brodny, J. (2021). Multi-Criteria Method for the Selection of Renewable Energy Sources in the Polish Industrial Sector. *Energies*, 14(9), 2386. https://doi.org/10.3390/en14092386

Valderrama, C. V., Santibanez-González, E., Pimentel, B., Candia-Véjar, A., & Canales-Bustos, L. (2020). Designing an environmental supply chain network in the mining industry to reduce carbon emissions. *Journal of Cleaner Production*, 254, 119688. https://doi.org/10.1016/j.jclepro.2019.119688

Various authors, Pr. S. (2020). SimaPro database manual - Methods library. *PRé Sustainability B.V.*, 4.15.

Varun, Bhat, I. K., & Prakash, R. (2009). LCA of renewable energy for electricity generation systems—A review. *Renewable and Sustainable Energy Reviews*, 13(5), 1067–1073. https://doi.org/10.1016/j.rser.2008.08.004

Wang, X., Xu, Z., Qin, Y., & Skare, M. (2023). The role of digital technologies in firms' performance: A panel data study on family firms and SMEs. *Journal of Competitiveness*, 15(2), 151-166. https://doi.org/10.7441/joc.2023.02.08