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Qualitative-environmental selection of a belt conveyor used in a mining system

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Abstract
Sustainable operations in the mining sector are challenging. Therefore, various supporting techniques are being sought. The aim of this article is to develop a model to support product selection by considering both quality (customer satisfaction) and environmental aspects (environmental impact in LCA). The model was developed in five main stages, using the WASPAS (Weighted Aggregated Sum Product Assessment) decision support method and the life cycle assessment (LCA) method, as specified in ISO 14040. The model was tested using belt conveyors used in mining and industry. They were characterized by eight main criteria: conveyor length, belt width with scrapers, belt configuration, side rail height, conveyor mounting, conveyor adjustment height, hopper capacity, and belt speed. Seven main prototypes of these products were developed. Using the proposed model, rankings of the analyzed belt conveyors were developed. Selection decisions were considered according to an aggregated quality-environmental indicator. The proposed model has been applied in the context of sustainable development activities in the mining sector. However, it can be applied to any product across various economic sectors.

Keywords
product quality, LCA, environmental impact, decision-making, mining, production engineering, mechanical engineering, efficiency

Introduction

Activities in the mining industry have social, environmental, and economic impacts on the surrounding area and society, as well as on the broader economic system and ecosystems. Positive effects include job creation, the development of technical infrastructure, and the stimulation of regional development by generating revenue from taxes and mining fees (Carvalho, 2017; Pacana & Siwiec, 2021; Korzynski et al., 2009). Some of these activities are positive, primarily in the socio-ecological context (Nuong et al., 2011). However, many negative impacts arise, particularly in the area of environmental conditions. This applies to sustainable development, but meeting these expectations in the expected form is problematic (Burmistrov & Osintsev, 2020). Mining, especially in peripheral regions, often forms the foundation of the local economy, contributing to improved living standards and social investment. However, the dominant aspect of research is the negative consequences of mining activities, especially in the environmental context (Bogusz & Sulich, 2020). Mining leads to landscape degradation, soil erosion, biodiversity loss, and pollution of surface and groundwater through the discharge of mine water containing heavy metals and sulfates (Awuah-Offei & Adekpedjou, 2011). Furthermore, dust and greenhouse gas emissions from raw material extraction and processing contribute to climate change (Dino et al., 2020).

From a sustainable development perspective, mining poses a particular challenge. Although modern technologies are being implemented to reduce negative environmental impacts (e.g., post-mining land reclamation, closed-loop water and sewage management, and emission monitoring), in practice, they often prove insufficient. The challenge lies in reconciling the growing demand for mineral resources with the need to minimize environmental degradation and maintain a high quality of life for local communities (Burchart-Korol et al., 2016; Hilson & Murck, 2000a; Siwiec et al., 2023).

The authors of the article by Tan et al. (2012) analyzed the role of ecological security in the sustainable development of mining. They analyzed the factors limiting uranium mining from the perspective of the aforementioned ecological security. In the study by Zhang et al. (2008), the importance and limitations of mining area development were analyzed. According to the theory of sustainable development, a system is created that provides a theoretical framework supporting the harmonious development of this area. Another example is the work of Hung et al. (2008), who assessed the sustainable development of mining towns. They developed economic sustainability indices using factor analysis. They identified economic benefits for enterprises and proposed development directions to increase investment in fixed assets. Another example is the work by Hilson & Murck (2000b), which analyzed sustainable development from a corporate mining perspective. They established guidelines for mining companies to support their sustainable operations. In turn, the article by Burmistrov & Osintsev (2020) developed the concept of sustainable development of mining-technical systems. Transition periods for open-pit mining were analyzed. This was based on systematizing existing principles of sustainable development in mining through a literature review and systems analysis. The authors of the study by Bascetin et al. (2016) proposed a combined approach integrating the assessment matrix and decision support methods (TOPSIS). This approach assessed the impact of mining on sustainable development. Furthermore, the article by Nuong et al. (2011) presented a method for assessing sustainable development in the mining sector using the AHP (Analytic Hierarchy Process) and the fuzzy FAHP methods. They discussed potential and practical approaches used in the mining sector.

It has been observed that there is a lack of research on techniques supporting operations in the mining sector. Some studies have used decision-support techniques, for example, but these have not addressed the selection of mining products while considering sustainability. Therefore, the aim of this article was to develop a model to support product selection that considers both qualitative (customer satisfaction) and environmental (LCA-based environmental impact). The model was tested using belt conveyors used in mining and industry as an example.

The model's originality lies in its qualitative and environmental index analysis, which aggregates results to support decision-makers in product selection. These decisions are based on a methodical approach to the combined assessment of product quality and environmental impact, in accordance with ISO 14040. Ultimately, a quality-environmental index (QLCA) is created. The proposed model can be useful not only in the mining sector but also in industry for selecting any product.

Materials and Methods

The research method is based on a developed model for supporting quality and environmental decision-making during product selection. The model concept encompasses an integrated approach to analyzing product quality and its environmental impact. The model aims to support decision-makers such as designers, technologists, and managers in selecting the most advantageous product from among the alternatives under consideration. These decisions are based on both qualitative and environmental assessments, where quality is understood as meeting customer requirements (satisfaction with product use), while the environment is defined by environmental impact throughout the product's life cycle. The approach involves searching for the most advantageous product from a quality and environmental perspective among various product alternatives—that is, products with the same application but characterized by different parameters (specifications).

The model implements the WASPAS (Weighted Aggregated Sum Product Assessment) decision support method (Weighted Aggregated Sum Product Assessment) (Zavadskas et al., 2012) and the life cycle assessment (LCA) method. WASPAS was used to assess product quality. LCA was used to assess environmental impact. WASPAS was chosen for its suitability for multi-criteria decision-making, which provides a comprehensive assessment framework that considers the importance (weights) of criteria and their quality assessments (Pacana et al., 2016; Thakkar, 2021). This method is based on the assumptions of the WSM (Weighted Sum Model) and WPM (Weighted Product Model) methods, which are used in product analyses (Zavadskas et al., 2014; Zhao & Shu, 2024). The WASPAS methodology requires the use of weighted and geometric aggregation operators to perform analyses in a fuzzy decision environment (Zavadskas et al., 2012). The LCA method, in turn, is based on the ISO 14040 standard (Finkbeiner et al., 2006) and provides an environmental assessment of a product or process according to selected environmental burden categories. Traditionally, this assessment is performed using a "cradle-to-grave" approach that encompasses stages of material acquisition and extraction, production, use, and end-of-life (Lagerstedt et al., 2003). The life cycle assessment phases in ISO 14040 are based on defining the purpose and scope of the study, inventory analysis, impact assessment, and interpretation of results (Pryshlakivsky & Searcy, 2013). Ultimately, the model was developed in five stages, namely:

1. Product selection and definition of product criteria for analysis.
2. Development of alternative product solutions.
3. Qualitative assessment of product alternatives.
4. Environmental assessment of product alternatives.
5. Quality-environmental aggregation and interpretation of results.

The procedure in the model is presented in Figure 1.
A synthetic description of the method's individual steps is presented later in the paper.

Stage 1. Product selection and definition of product criteria for analysis. Any product can be selected for analysis. It should be a physical product. Product selection rests with the expert using the offered model, e.g., a manager, designer, or technologist. The decision to select a product may be driven, for example, by the need to purchase a new product or the expansion of a product offering. This product will be considered in the remaining stages of the model, where various alternatives will be analyzed. Therefore, to evaluate one product type (kind) against various product solutions, it is proposed to define key product criteria. These criteria should address qualitative and environmental aspects. Criteria belonging to the qualitative aspect are understood as technical (measurable) criteria included in the product specification (catalog) (Pacana & Siwiec, 2022; Siwiec & Pacana, 2021). These criteria characterize the product in the context of customer assessment of its usability, e.g., weight, size, and power. The criteria are defined by a team of experts selected based on the literature, e.g., Kupraszewicz & Żółtowski (2002) and Nemeshaev et al. (2021). Furthermore, criteria related to the environmental aspect are proposed as a criterion for the environmental impact of a product throughout its life cycle (Dyson, 2024). It is assumed that the environmental assessment depends on a single selected environmental criterion, e.g., carbon dioxide emissions (CO_2) (González & García Navarro, 2006). The sum of all quality and environmental criteria in medium-complex products ranges from 10 to 15 (Kolman, 1992).

Stage 2. Developing alternative product solutions. Different products with the same application are sought. These products are characterized by different parameters (specifications). Within the proposed model, it is possible to base their subsequent production on existing products or on developed alternative product solutions (Siwiec & Pacana, 2022). This involves developing various states of quality criteria, i.e., different specifications for individual criteria from stage 1. These states are determined by a team of experts. States are expressed in the form of immeasurable or measurable values, e.g., a value or a range of values. Following the authors (Mu & Pereyra-Rojas, 2017), it is beneficial to develop approximately five to ten product prototypes.

Stage 3. Qualitative evaluation of product alternatives. Product alternatives (prototypes) are evaluated in terms of meeting customer expectations (Ostasz et al., 2022). This is an assessment of the product quality level. All product alternatives developed in Stage 2 of the model are rated. Ratings are assigned by a panel of experts using a five-point Likert scale (Koo & Yang, 2025; Sullivan & Artino, 2013). The ratings are then presented as decimal values.

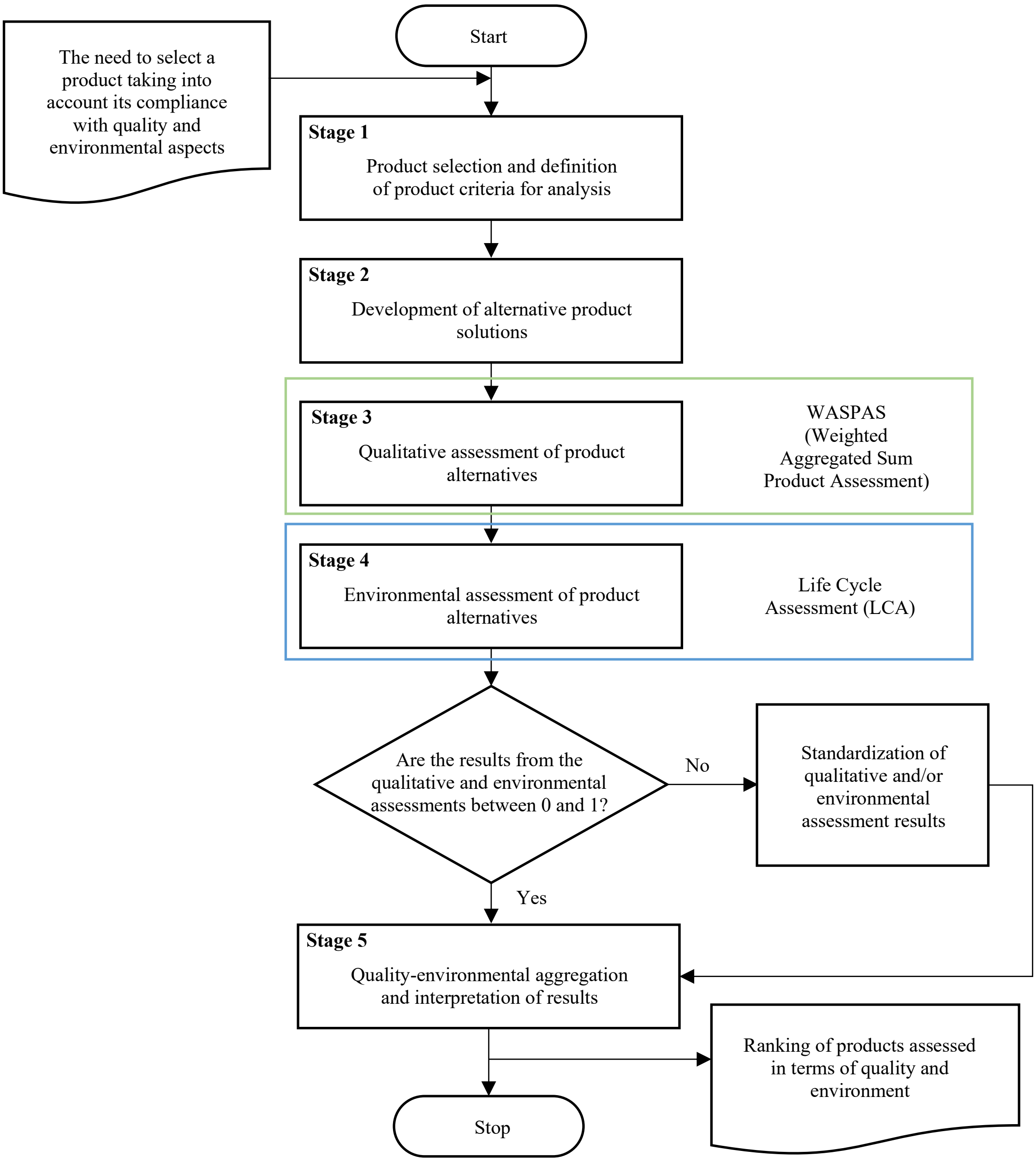

Fig. 1. Schematic diagram of the product selection model from a quality-environmental perspective.

The ratings are assigned by a panel of experts. The WASPAS method is used, according to formulas (1-4) (Thakkar, 2021; Zavadskas et al., 2012, 2014):

$$\mathbf{Q_i^1 = \sum_{j=1}^{n} w_j x_{ij}} \tag{1}$$

$$\mathbf{Q_i^2 = \prod_{j=1}^{n} {x_{ij}}^{w_i}} \tag{2}$$

$$\mathbf{Q_i = \lambda Q_i^1 + (1 - \lambda) Q_i^2} \tag{3}$$

$$\mathbf{Q_i = \frac{Q_i - \min Q}{\max Q - \min Q}} \tag{4}$$

i.e.: w – weight of the product criterion, x – quality assessment of the product criterion, λ – coefficient from 0 to 1, i,j = 1,…,n.

The quality indicator (Q) values should range from 0 to 1, with higher values indicating that customer expectations are better met.

Stage 4. Environmental Assessment of Product Alternatives. The environmental impact of the product prototypes under consideration is assessed using the LCA method. This is conducted by a team of experts using the ISO 14040 method (Finkbeiner et al., 2006). During life cycle assessment, it is essential to define the system boundaries. It is assumed that the assessment will be carried out "from cradle to grave," taking into account the stages of material acquisition and extraction, products, use, and end-of-life (Neramballi et al., 2020). Furthermore, a functional unit is defined to normalize data. A functional unit is a quantitative measure of the product system. It ensures a fair comparison of different systems for the same end function. The functional unit should be defined so that it is easily measured and quantified throughout the entire life cycle (Yao et al., 2021). In the proposed model, the assessment is conducted according to a single environmental burden criterion, selected, for example, based on the product type. LCA can be performed using a computer program, such as OpenLCA (Pacana et al., 2023). The obtained results should be normalized to a value between 0 and 1. A qualitative indicator also takes values between 0 and 1, so to aggregate the results, it is necessary to scale the environmental assessment results to these values. Formula (5) is used for this purpose:

$$\mathbf{LCA_i} = \frac{\mathbf{max\,LCA - LCA_i}}{\mathbf{max\,LCA - min\,LCA}} \tag{5}$$

The higher the value of the environmental indicator, the greater the negative environmental impact of the product.

Step 5. Quality and environmental aggregation and interpretation of results. The final step of the model is to aggregate the quality and environmental assessment results into a single decision indicator (QLCA). Product selection can then be made while considering both quality and environmental aspects. Aggregation is performed according to formula (6):

$$\mathbf{QLCA_i} = \mathbf{Q_i} + \mathbf{LCA_i} \tag{6}$$

where: Q – qualitative indicator, LCA – environmental indicator, i = 1,2,…,n.

A ranking of prototypes is created based on the QLCA (quality and environmental assessment) index. The higher the QLCA value, the more favorable the prototype. The first position in the ranking is the prototype with the maximum index value. The most favorable prototype is one characterized by both the highest possible fulfillment of customer requirements (quality) and the lowest possible negative environmental impact throughout the life cycle. According to a dedicated model, the first position represents the best product choice. However, it is possible to choose a different product from the ranking, and this choice could be dedicated to, for example, company resources.

Results

The model was tested using a belt conveyor used in mining and industrial applications. A conveyor is a fundamental machine for transporting bulk materials, lump materials, and unit loads over distances ranging from a few meters to several kilometers. This transport occurs in a horizontal or inclined plane. A conveyor system includes many moving parts, and wear and friction are inevitable (Hakami et al., 2017). Using a belt conveyor, material can be loaded and unloaded at any location the user prefers. The belt can move unidirectionally or bidirectionally. Belt conveyors typically have fabric, rubber, or PVC belts. Conveyor belts are used in mines, ports, and cement plants, primarily due to their structural and physical adaptability (Bolton, 2015; Hakami et al., 2017).

The belt conveyor was characterized by key quality criteria. These were selected based on the product catalog and literature reviews, e.g., Awuah-Offei et al. (2009), Bolton (2015), Chaulya & Prasad (2016), Hakami et al. (2017), and Verakis (2006). Eight main criteria were selected: conveyor length, belt width with scrapers, belt layout, side rail height, conveyor mounting, conveyor adjustment height, hopper capacity, and belt speed. Hypothetical product solutions (prototypes) for belt conveyors were developed, based on existing products and literature reviews, e.g., (Awuah-Offei et al., 2009). Due to the specific nature of belt conveyors, the development of anticipated, beneficial product solutions was limited to seven prototypes (Table 1).

Tab. 1. Conveyor belt prototypes

Prototypes	Conveyor length (mm)	Belt width with scrapers (mm)	Tape layout	Side rail height (mm)	Conveyor mounting	Conveyor adjustment height (mm)	Hopper capacity (l)	Belt speed (m/s)
P1	4500	400	Single-roller	150	Mobile	1600-2400	50	0.5
P2	4600	450	Two-roller	140	Stationary	1500-2500	60	0.7
P3	4700	500	Two-roller	160	Mobile	1600-2300	70	0.7
P4	4600	400	Single-roller	130	Stationary	1400-2500	50	0.6
P5	4500	450	Two-roller	160	Stationary	1700-2600	40	0.5
P6	4300	600	Single-roller	150	Mobile	1800-2400	60	0.5
P7	4400	550	Two-roller	170	Stationary	1600-2400	70	0.6

Source: own elaboration.

A qualitative assessment of product alternatives was conducted using the WASPAS method. To this end, the importance of belt conveyor criteria was assessed, as was the fulfillment of customer requirements based on the offered criteria. Ratings were assigned on a five-point Likert scale and subsequently reduced to decimal values. The results are presented in Table 2.

Tab. 2. Evaluation criteria for belt conveyors.

Prototypes	Conveyor length (mm)	Belt width with scrapers (mm)	Tape layout	Side rail height (mm)	Conveyor mounting	Conveyor adjustment height (mm)	Hopper capacity (l)	Belt speed (m/s)
Weight	0.5	0.5	0.3	0.3	0.2	0.4	0.4	0.3
P1	0.4	0.3	0.4	0.4	0.5	0.4	0.4	0.4
P2	0.5	0.4	0.5	0.5	0.4	0.3	0.4	0.5
P3	0.5	0.4	0.5	0.3	0.5	0.4	0.5	0.5
P4	0.5	0.3	0.4	0.5	0.4	0.2	0.4	0.4
P5	0.4	0.4	0.5	0.3	0.4	0.5	0.3	0.4
P6	0.3	0.5	0.4	0.4	0.5	0.5	0.4	0.4
P7	0.4	0.5	0.5	0.3	0.4	0.4	0.5	0.5

Source: own elaboration.

Next, based on the prototype evaluations, calculations were made using formulas (1-4). The coefficient λ=0.5 was assumed. The partial indicator results (Q1, Q2) were normalized to values between 0 and 1. The belt conveyor prototypes were ordered according to the estimated quality indicator (Q). The results from the WASPAS method are presented in Figure 2.

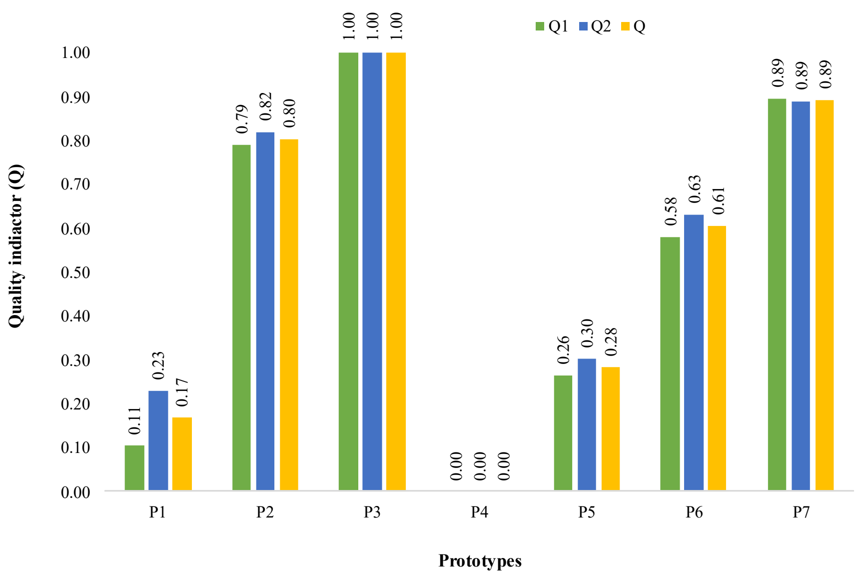

Fig. 2. Results of qualitative analysis of belt conveyor prototypes according to the WASPAS method.

According to the qualitative assessment, prototype P3 proved to be the most advantageous. It achieved the highest quality index (Q = 1.00). It is characterized by the criteria parameters that best meet customer requirements. Prototype P7 is next in the ranking (Q = 0.89), with P2 having a slightly lower quality index (Q = 0.80). Considering only the qualitative aspect, the choice is made among belt conveyors designated P3, P7, and P2.

Next, an environmental analysis of the belt conveyors was performed. The assumptions were adopted from the study by Awuah-Offei et al. (2009), which assumes an availability of 85% for the belt conveyor system. The functional unit is the transport of approximately 4,000 tons/h. The simplified system boundaries are "from cradle to grave," where the product system is presented in Figure 3.

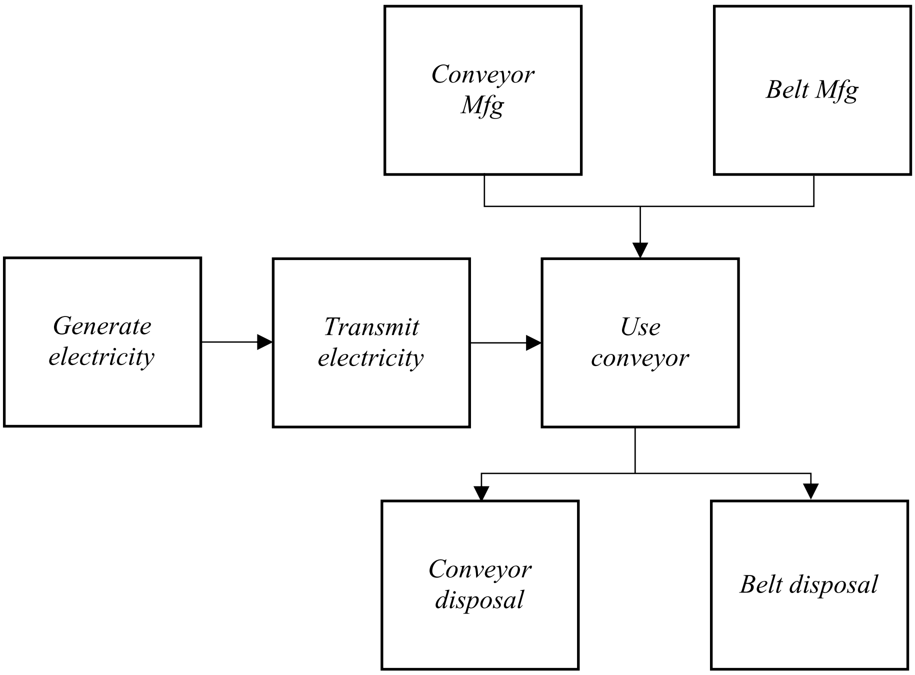

Fig. 3. Product system for belt conveyors.
Source: own elaboration based on (Awuah-Offei et al., 2009).

The LCA analysis included carbon dioxide (CO_2) emission criteria. To illustrate the model, the environmental impact of the prototypes over their life cycle was estimated following the authors' approach (Awuah-Offei et al., 2009). It was conventionally assumed that individual prototypes could have an environmental impact ranging from 1,500 to 4,000 eq. kg CO_2. The team of experts, including the authors of the article, conventionally estimated the environmental impact results for the developed belt conveyor prototypes: P1: 3600 eg. kg CO_2; P2: 3550 eg. kg CO_2; P3: 3500 eg. kg CO_2; P4: 3400 eg. kg CO_2; P5: 3800 eg. kg CO_2; P6: 4000 eg. kg CO_2; P7: 3700 eg. kg CO_2. The environmental indicator results were normalized using formula (4). The ranking is presented in Figure 4.

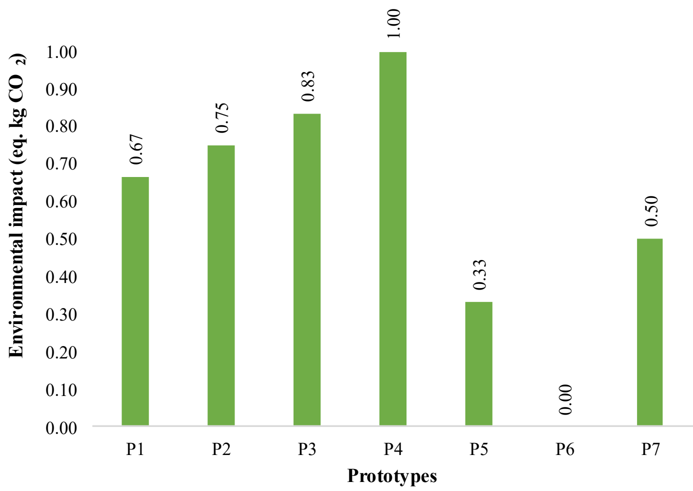

Fig. 4. Hypothetically estimated LCA for conveyor belt prototypes.

Based on the estimated LCA index, prototype P4 is predicted to have the lowest negative environmental impact (LCA = 1.00). Prototype P3 is next (LCA = 0.83), followed by P2 (LCA = 0.75). The highest negative environmental impact is predicted for prototype P6. Precise environmental assessment results can be achieved by performing real-world calculations using, for example, a computer program such as OpenLCA. Currently, these estimates are presented as part of the model test.

As part of the simultaneous qualitative-environmental analysis, the qualitative and environmental indicators were aggregated. Formula (6) was used. The ranking of prototypes according to the QLCA index is presented in Figure 5.

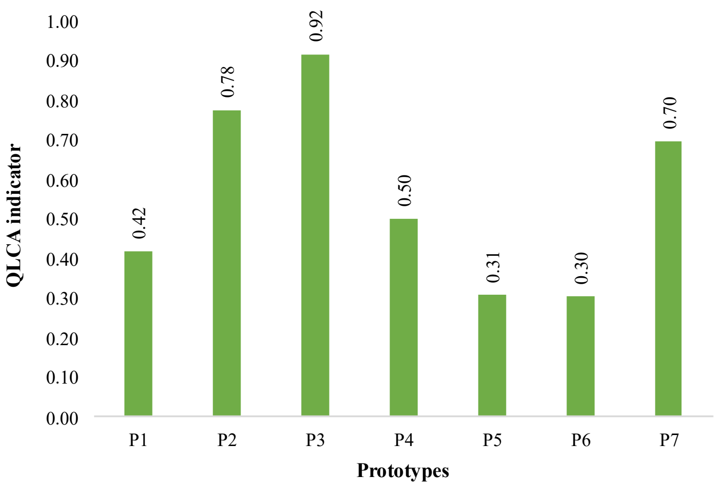

Fig. 5. Estimated QLCA for conveyor belt prototypes.

Based on the proposed model, it was demonstrated that choosing the belt conveyor conventionally designated P3 (QLCA = 0.92) was advantageous. It is characterized by the expected quality level and is relatively environmentally friendly throughout its life cycle. It ranked first in the quality ranking, while second in the environmental ranking. Aggregating the results, this prototype was deemed the most advantageous. Next in the ranking is prototype P2 (QLCA = 0.78), ranking third in both the quality and environmental rankings. Next, it is proposed to consider prototype P7 (QLCA = 0.70). It ranked second in the quality ranking and fifth in the environmental ranking. It can be observed that the quality indicator has a significant impact on the final ranking of belt conveyor prototypes according to the QLCA. The final decision regarding the most advantageous belt conveyor prototype depends on the entity using the model. It may depend on the company's individual needs, including financial resources and efficiency.

Discussion and Conclusions

Sustainable product development requires the use of various supporting techniques. These techniques are primarily sought in complex development decisions. Techniques that would allow for a systematic assessment of selected aspects of sustainability are still lacking. Therefore, the aim of this article was to develop a model that supports product selection by simultaneously considering qualitative (customer satisfaction) and environmental (LCA-based environmental impact) aspects. The model's concept involves identifying the most advantageous product solutions, considering both customer satisfaction with product use and product life-cycle assessment. The model was developed in five main stages: (1) product selection and definition of product criteria for analysis, (2) development of alternative product solutions, (3) qualitative assessment of product alternatives, (4) environmental assessment of product alternatives, and (5) qualitative and environmental aggregation and interpretation of results. The model implements the WASPAS (Weighted Aggregated Sum Product Assessment) decision-support method and the LCA method as specified in ISO 14040.

The method was tested and illustrated using belt conveyors used in mining and industrial applications. Seven prototypes of these products were developed, taking into account criteria such as conveyor length, belt width with scrapers, belt layout, side rail height, conveyor mounting, conveyor adjustment height, hopper capacity, and belt speed. The prototypes were evaluated using the WASPAS method. Prototype P3 proved to be the most advantageous. Next, the environmental impact of the prototypes over their life cycle was assessed for the environmental burden criterion – carbon dioxide emissions. Prototype P4 was predicted to have the lowest negative impact. By aggregating the results, it was possible to predict the most advantageous product solution. In accordance with the adopted assumptions, the belt conveyor prototype that demonstrated the expected level of quality and, at

the same time, a relatively low negative environmental impact was prototype P3. The model proved effective in product quality and environmental analysis.
The main benefits of the offered model include:

- Support in development decisions regarding product selection;
- Providing qualitative analyses to ensure customer satisfaction with product use;
- Supporting product life cycle assessments based on selected environmental criteria;
- Aggregating product quality and environmental indicators;
- Optimizing development activities focused on meeting customer expectations and protecting the natural environment throughout the product life cycle;
- Reducing resource waste by clarifying decision-making.

However, one limitation of the model is its focus on environmental analyses based on a single environmental impact criterion. Furthermore, the model allows verification of only a limited number of prototypes, which risks missing the optimal solution in a given analysis. At the same time, this model does not extend the analyses to include other aspects, such as costs or social impact.

Therefore, future research will include expanding the model to include analyses based on a larger number of environmental impact criteria. It is also planned to incorporate additional sustainability aspects into the model. Future research will also explore the use of artificial intelligence algorithms to predict product solutions dynamically.

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