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Sustainable Product Development Considering Quality, Cost and Life Cycle Assessment (QC-LCA)

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Abstract
The study aimed to develop a procedure based on the QC-LCA indicator to support product-development decisions at the early design stages. The procedure guides the creation and evaluation of product prototypes by generating alternative design solutions during the design or improvement phase. It follows a five-step methodological framework that prospectively assesses: i) prototype quality, ii) life-cycle environmental impact (LCA), and iii) production costs. The procedure employs several techniques, e.g. the TOPSIS method, brainstorming (BM), the 7±2 rule, and ISO 14040. Results from the main stages produce quality, cost, and environmental indicators, which are then aggregated into the QC-LCA indicator. This indicator forms the basis for ranking the product prototypes.

Keywords
LCA; Quality; Sustainable Product Development; QLCA; Mechanical Engineering; ISO 14040.

Introduction

Sustainable product development should be guided by informed decisions that promote efficient resource use (Kumar et al., 2019; Tomashuk et al., 2023). This includes reducing environmental pollution, minimizing waste, and avoiding financial losses caused by imprudent production (Lamolinara et al., 2022; Rodríguez-Olalla & Avilés-Palacios, 2017; Vásquez et al., 2018). Equally important is incorporating the voice of customers (VoC) at every development stage to maximize product satisfaction (Li et al., 2023; Pacana et al., 2024; Rihar & Kušar, 2021; Siwiec & Pacana, 2024a). Gathering customer requirements accurately is essential for coping with rapidly changing markets (Rihar & Kušar, 2021; Siva et al., 2016; Ulewicz et al., 2023). Moreover, enterprises must consider economic factors to function effectively; sound financial management fosters growth and helps firms attain their desired market position (Trueba-Castañeda et al., 2024).

A literature review reveals that product design and improvement still focus on quality – that is, increasing customer satisfaction. Although environmental and cost considerations are now receiving more attention, consistent techniques and methodologies that integrate all key aspects of sustainability remain rare.

Accordingly, the study aimed to develop a QC-LCA-based procedure to guide product-development decisions at the earlies stages. The procedure can assist designers, managers, and other decision-makers during conceptualisation, prototyping and design, as well as when improving products already on the market. By combining quality, cost, and life-cycle assessment into a single QC-LCA indicator, the approach offers a broader perspective than traditional design-thinking methods, thereby promoting truly sustainable product development.

Literature review

A systematic review of major publications on product sustainability was conducted, taking into account three key criteria: quality (customer satisfaction), environmental impact, and costs. The initial search term used was "sustainable product development", which was identified in the title, abstract, and keywords of publications. This search yielded over 305 thousand documents. Therefore, it was necessary to introduce limitations to increase the reliability and structure of the review. The first limitation involved narrowing the

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scope to works containing the terms "sustainable product development", and "quality", and "environmental impact" simultaneously. This refinement resulted in 538 publications. The next step was to limit the selection to open-access works, reducing the pool to 193 documents. These were then subjected to expert analysis, which involved assessing each title and abstract for relevance to the research topic-specifically, sustainable product development in terms of design and improvement. Ultimately, 37 works met the established criteria. The bibliometric analysis included an examination of publication types, the number of publications per year, research areas, keywords, and citations counts. The content review aimed to identify the research scope within the thematic area, including the specific product development phases addressed.

Among the 37 selected works, there were 31 journal articles, 5 conference papers, and 1 literature review (Fig. 1).

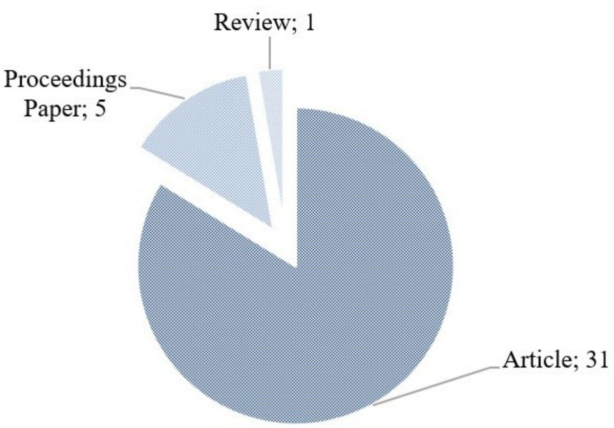

Fig. 1. Type of study

The predominance of journal articles highlights the academic importance of the topic and reflects the growth of the research field. The presence of conference papers suggests that the topic is also being addressed in practical applications.

Next, the research areas related to the analysed topic were analyzed (summarized in Table 1).

The main research areas included Environmental Sciences & Ecology (15), Engineering (14), and Science & Technology – Other Topics (13), indicating that the subject spans both environmental and engineering disciplines. Additional fields included Business & Economics (6) and Materials Science (5), with occasional studies in energy, metallurgy, and geology.

The selected works were also analyzed for publication frequency by year to observe trends in the development of the research area. The results are presented graphically in Figure 2. The field of sustainable product development, particularly its design and improvement, appears to be in a growth phase.

Table 1
Main research areas

Research area	Number
Environmental Sciences & Ecology	15
Engineering	14
Science & Technology – Other Topics	13
Business & Economics	6
Materials Science	5
Chemistry	3
Energy & Fuels	3
Physics	3
Metallurgy & Metallurgical Engineering	2
Automation & Control Systems	1
Geology	1

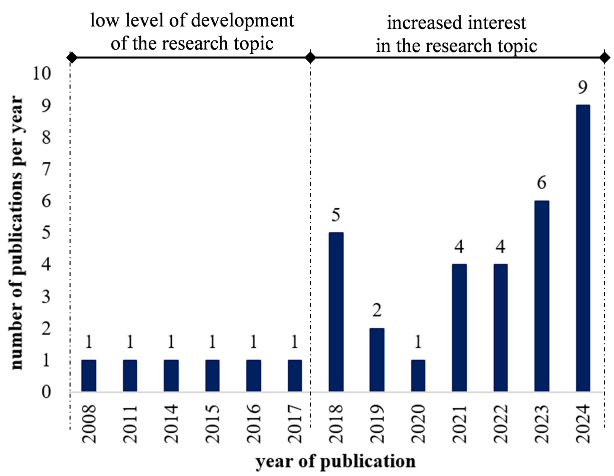

Fig. 2. Number of publications per year with developmental interpretation

The first publication on this topic appeared in 2008, followed by only one publication annually until 2017, indicating limited interest. However, in 2018, the number of publications rose to five, possibly driven by initiatives promoting energy efficiency and environmental responsibility. This growth may also reflects increasing market demands for environmentally friendly solutions, technological innovations, and evolving regulatory frameworks. While the number of publications declined in 2019-2020, a notable resurgence occurred from 2021 to 2024 (as of October), confirming renewed and growing interest the topic. The relatively small number of publications overall highlights the existence of many research gaps, offering opportunities for further exploration.

The authors' keywords were analyzed to identify the main themes. Across the 39 works, 208 keywords were found (including duplicates), representing 144 unique terms. A word cloud was created using WordArt to visualize keyword frequency (Fig. 3).

Fig. 3. Author keyword cloud

The larger the font size, the more frequently the term appeared. The most common keywords included: sustainable, product, design, green, life, and quality, etc. Further analysis focused on keywords that appeared at least nine times, as shown in Table 2.

Table 2
Main research areas related to the topic

Keyword Phrase	Number
Sustainable Development	11
Production Engineering	10
LCA, Life Cycle Assessment, Life-Cycle Assessment	10
Mechanical Engineering	9
Quality	9
Sustainability	9

The most frequent term was "sustainable development" (11), though this may reflect the original search query. Other frequently occurring terms included "production engineering" (10) and "life cycle assessment", often noted in its acronym form (LCA, Life-Cycle Assessment) (10). This indicates a strong connection between sustainable product development and LCA, as well as with production engineering. Mechanical engineering (9), quality (9), and sustainability (9), were also prevalent, reinforcing the emphasis on customer satisfaction as a key aspect of sustainability. Less frequent terms included "quality management" (4), innovation (3), and AHP (3). Keywords that appeared once or twice were excluded from detailed analysis, but remain visible in the word cloud.

The content of the selected works was then reviewed to identify their primary focus and application area. A summary is presented in Table 3.

Table 3
Summary of the content analysis of the subject

Thematic scope	Publication
Prototyping (design and improvement)	
Supporting product sustainability by simultaneously considering product quality (customer expectations) and environmental impact, including LCA and/or costs	(Kang & Nagasawa, 2023; Li et al., 2023; Pacana et al., 2023, 2024; Pacana & Siwiec, 2023, 2024; Rihar & Kušar, 2021; Siva et al., 2016; Siwiec et al., 2024; Siwiec & Pacana, 2021b, 2024a, 2024b, 2024c; Ulewicz et al., 2023)
Ensuring sustainable use of resources to reduce environmental pollution in the form of waste prevention and financial gain	(Kumar et al., 2019; Lamolinara et al., 2022; Rodríguez-Olalla & Avilés-Palacios, 2017; Tomashuk et al., 2023; Vásquez et al., 2018)
Linking sustainability competencies with quality management practices, including exploring their integration and personalization	(Gremyr et al., 2014; Siva et al., 2018)
Concept-based decision support, e.g. LCA and eco-design for sustainable product development	(Kulatunga et al., 2015; Romli et al., 2018; Zhang et al., 2018)
Defining eco-efficient product requirements to meet customer requirements	(Menon & Ravi, 2021)
Creating product and process innovations	
Analysis of environmental innovations including product and process innovations in sustainable development of enterprises including environmental, social and economic dimensions	(Boavida et al., 2020; Hernandez-Vivanco et al., 2018; Vrabcova & Urbancova, 2021; Zhao et al., 2023)
Improvement activities and company functioning	
Determining the relationship between positive financial results from Industry 4.0 and the ability to achieve sustainable development	(Trueba-Castañeda et al., 2024)

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Thematic scope	Publication
Analysis of the competitiveness of environmentally friendly products with traditional products, including verification of the quality of these products based on economic attributes	(Tran et al., 2022; Yin et al., 2019; Zhang & Zhang, 2022)
Integration of LCA and life cycle costing to identify, assess and model the impact of sustainability risks specific to product life cycle characteristics	(Siva et al., 2016)
The impact of product and process innovation and the circular economy on organizational performance and sustainable development of enterprises	(Severo, 2024)

It was observed that sustainable product development efforts typically occur during the early stages of product development, such as conceptualisation and prototyping (including design and improvement). Previous analyses have considered qualitative, environmental, and financial factors, often incorporating quality management, personalization, innovation, and eco-efficiency.

Based on the literature review, the following conclusions were drawn :

- The research area primarily falls within environmental and engineering sciences.
- The field is still developing, with a relatively small number of publications pointing to significant research gaps, and potential for further study.
- Sustainable product development in the form of design and improvement is closely linked to LCA and production engineering.
- Supporting sustainable product development from the earliest stages is crucial and should include considerations of quality, environmental impact, and cost.

It was also observed that product design and improvement are traditionally focused on meeting customer requirements, i.e. achieving the desired product quality. However, the increasing awareness of climate change and public health concerns is shifting the focus toward sustainability. This shift involves integrating sustainable development criteria, particularly quality, environment, and costs.

Despite this trend, sustainable product development practices in manufacturing companies remain poorly defined and unstandardized. There is still a lack of consistent techniques and methodologies to support product development while addressing key sustainability criteria. This gap in the literature was basis for developing a procedure based on the QC-LCA indicator, which is presented in the following section of the paper.

Methods

A procedure based on the QC-LCA indicator was developed to support decision-making in the early stages of product development (concept, design, and prototyping). The acronym QC-LCA refers to the integrated aspects of sustainable development, i.e.: Q – quality, C – cost, LCA – Life Cycle Assessment. These aspects serve as the basis for determining the direction of sustainable product development. The procedure consists of five steps and it compatible with the traditional design thinking approach (Chen & Venkatesh, 2013), as illustrated in Figure 4. Each step of the procedure is described below.

Stage 1. Product selection and prototyping

The product selected for analysis is optional and depends on the needs of the entity applying the method.

It may already be in the maturity phase and require improvement due to changing market conditions. It is recommended to choose a product that is well-known and widely used by customers, increasing the likelihood of accurately identifying customers requirements in the subsequent stages. The product is characterized by key criteria that significantly affect customer satisfaction. Up to ten main criteria should be selected (Mu & Pereyra-Rojas, 2017) by a team of experts, which can be assembled using methods such as those proposed by (Halvorsen, 2013). The team may work using brainstorming techniques (BM). Based on available list of product characteristics (e.g., in a specification catalog), key (main) criteria – those most directly linked to customer satisfaction, such as weight, color, size, or power, etc. – are selected. Market trends, changes in customer needs, and past improvement activities should also inform the selection. Each criterion is described in terms of its current state (as implemented in the product) and its modified states (hypothetical, alternative design solution) (Siwiec & Pacana, 2021a). These alternatives may involve changes in value (higher or lower) or qualitative differences. A minimum of 7 ± 2 variants per criterion is recommended (Mu & Pereyra-Rojas, 2017). The resulting set of criteria and states represents the current product and its prototypes (alternative design solutions).

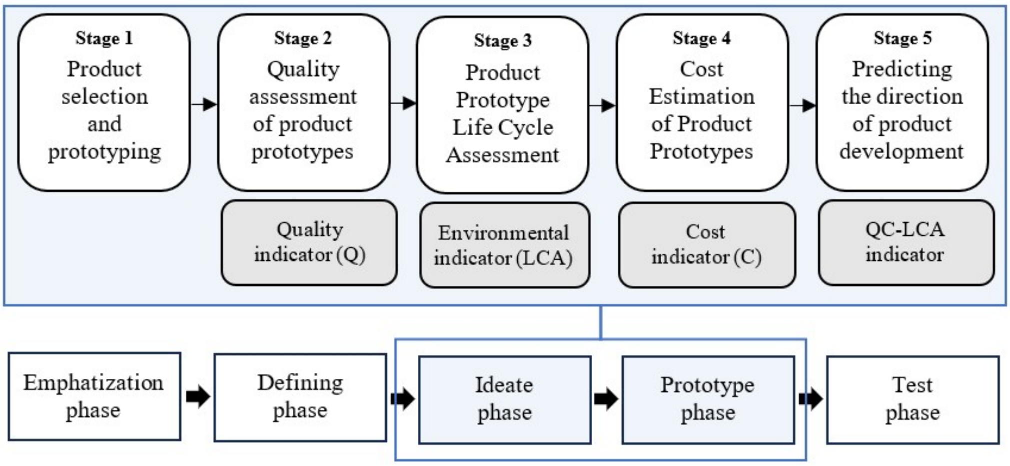

Fig. 4. Scheme of procedure based on QC-LCA indicator and its application in design thinking.

Stage 2. Quality assessment of product prototypes

The current product and its prototypes are evaluated by customers, for example through surveys or interviews. The sample size can be estimated using methods described by (Hyman & Sierra, 2016; Memon et al., 2020; Siwiec & Pacana, 2021a). The aim is to assess perceived product quality. Customers rate both the importance of each product criterion and their satisfaction with its current or modified state, using a scale: 1 – criterion practically insignificant or the status of the criterion practically does not meet the requirements, 5 – criterion absolutely most important or the status of the criterion fully meets the requirements. An arithmetic mean is calculated to represent the average weight (importance) and satisfaction level for each criterion. These averages are processed using a selected method for product quality evaluation, depending on the organization's preferences. Ultimately, a quality indicator (O) is obtained for each prototype; the higher the value, the better the quality.

Stage 3. Product Prototype Life Cycle Assessment

Life cycle assessment (LCA) is carried out in accordance with ISO 14040 (Finkbeiner et al., 2006). LCA evaluates a product's environmental impact across its life cycle, covering phases such as material acquisition, production, use, and end-of-life ("cradle-to-grave") (Gajdzik et al., 2024; Siwiec et al., 2025). The current and prototype products are treated as a reference product – a generalization of similar products. Inventory data and a functional unit are established to normalize the dat a for comparison. System boundaries are defined to include all LCA phases. Software tools like OpenLCA or SimaPro can be used to perform the assessment for the current product. Based on this, an environmental indicator (E) is determined. Experts then estimate the relative environmental impact of the prototypes, comparing them to the current product. A higher E value indicates a greater environmental burden.

Stage 4. Cost Estimation of Product Prototypes

Experts estimate the costs associated with producing the current product and its prototypes. For the current product, this includes actual production of purchase cost. These serve a baseline for estimating the costs of prototypes. The cost indicator (K) reflects these values. Based on the literature on the subject, e.g. (Chenavaz, 2012), suggests that quality improvements often lead to higher costs. However, investment in product development also influences cost policies, which are affected more by process changes than by quality itself. Because cost estimation approaches vary across enterprises, it is assumed that each organization will apply its own preferred method (Weustink et al., 2000). The higher the cost indicator value, the more expensive the prototype.

Stage 5. Predicting the direction of product development

The CQ-LCA-based procedure concludes with predicting the most sustainable direction for product development based on the evaluated prototypes. The optimal direction satisfies the three pillars of sustainability: quality (customer satisfaction with use), environmental impact in LCA, and costs incurred within the product. To aggregate the three indicators into one composite QC-LCA indicator, normalization is necessary since each indicator may span different numerical ranges. This step ensures fair weighting and interpretability. Normalization is especially important for the LCA values, which often exceed 1, compared to quality indicators, which typically range between 0 and 1. Without normalization, one indicator could dominate the overall results. According to the principle, the higher the value, the better for the quality indicator, and the higher the value, the worse for the environmental and cost indicator; normalization is carried out according to formula (1). The values of the Q, LCA and C indicators, according to the normalisation principle, should be in the range from 0 to 1, where 1 is the most favorable prototype in terms of the considered aspect, 0 is the least favourable prototype in terms of the considered aspect. The aggregation of normalized indicators is performed according to the formula (2). Prototypes are ranked according to their QC-LCA indicator. The prototype with the highest indicator value is considered the most sustainable option, providing the best trade-off between customer satisfaction, environmental impact, and cost If the top-ranked prototype is not feasible (e.g., due to organizational constraints), the next-best prototype should be considered. The final decision rests with the entity applying the procedure.

$$\begin{cases} \mathrm{Q}_j = \dfrac{O_j - \min O_j}{\max O_j - \min O_j} \\ \mathrm{LCA}_j = \dfrac{\max E_j - E_j}{\max E_j - \min E_j} \\ \mathrm{C}_j = \dfrac{\max K_j - K_j}{\max K_j - \min K_j} \end{cases} \tag{1}$$

where: O – quality indicator, E – environmental indicator, K – cost indicator, Q – standardized quality indicator, LCA – standardized environmental indicator, C – normalized cost indicator, j – prototype, $j = 1, 2, \ldots, n$.

$$\mathrm{QC-LCA}_j = \frac{\mathrm{Q}_j + \mathrm{LCA}_j + \mathrm{C}_j}{3} \tag{2}$$

where: symbols as in formula (1).

In the event that the prototype in the first place in the ranking cannot be considered expedient, e.g. due to the company's resources, the next prototype in the ranking should be considered. The final decision on the choice of the product development direction belongs to the entity that uses the proposed procedure. The presented procedure promotes sustainable product development and may be crucial at the initial stage of product development.

Results

The testing and illustration of the procedure based on the QC-LCA indicator were conducted for water-based topcoat paints used to create protective and decorative coatings inside buildings. These products were chosen due to their widespread use and significant impact on the natural environment. The paints came from a popular manufacturer. Six production variants were developed, conventionally labeled P1-P6 for the purposes of testing. The paints were evaluated according to five main criteria: efficiency, total drying time, drying time between layers, number of layers to full coverage, and resistance to scrubbing. All prototypes were standardized as five-litre matt paints. Based on the product catalogues, the states of these criteri a were proposed (Table 4).

Table 4
Paint prototypes

Criterion	P1	P2	P3	P4	P5	P6
efficiency (m^2/l)	16	16	17	15	10	14
total drying time (h)	28	4	24	3	36	4
drying time between layers (h)	4	1	3	1,5	3	2
number of layers to full coverage	1	2	1	2	2	1
resistance to scrubbing (class)	2	1	1	2	1	2

Next, as part of the pilot study and procedure validation, feedback was gathered from nine customers. This sample size was chosen solely for illustrative purposes and to verify the assumed methodology. In practical applications, a larger sample size is recommended to ensure more objective and representative results. Using a five-point Likert scale, the respondents assessed both the importance of the paint criteria and the proposed criterion states. Based on the customer ratings, the average quality value for each criterion state was estimated. The results are presented in Table 5.

In the proposed approach, the average values were processed using the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) (Bertolini et al., 2020), which calculated the quality indicator for the paint prototypes. This method was chosen for its simplicity and suitability for evaluating multiple alternative design solutions simultaneously (Chen, 2000; Kaur et al., 2016), supporting an efficient calculation process. According to the TOPSIS

Table 5
Average quality ratings of criteria states

Prototype	A1	A2	A3	A4	A5
weights	4.44	3.67	3.89	4.56	3.78
P1	4.44	3.89	2.56	5.00	3.67
P2	4.44	4.44	5.00	3.78	5.00
P3	5.00	3.89	3.67	5.00	5.00
P4	3.67	5.00	4.78	3.78	3.67
P5	2.67	2.56	3.67	3.78	5.00
P6	3.56	4.44	4.56	5.00	3.67

where: A1 – efficiency (m^2/l), A2 – complete drying time (h), A3 – drying time between layers (h), A4 – number of layers to full coverage, A5 – scrub resistance (class)

method, the normalized values of the criterion state were calculated based on the average quality values using formula (3):

$$\overline{q}_{ij} = \frac{q_{ij}}{\sqrt{\sum_{j=1}^{n} q_{ij}^2}} \tag{3}$$

where: q – the average value of the quality assessment of the i-th criterion condition, i – criterion, j – prototype, $i, j = 1, 2, \ldots, n$.

Subsequently, taking into account the average weights of the paint criteria, the weighted normalized quality values were computed using formula (4) (Bertolini et al., 2020):

$$\overline{wq}_{ij} = w_{ij} \times \overline{q}_{ij} \tag{4}$$

where: q – the average value of the quality assessments of the i-th criterion state, i – criterion, j – prototype, $i, j = 1, 2, \ldots, n$.

For each prototype criterion, the values of the ideal positive solution (V^+) and the ideal negative solution (V^-) were then determined. These represent the expected maximum and minimum values for each criterion, based on ideal solutions. The obtained results are presented in Table 6.

Next, the Euclidean distance to the best ideal solution (S^+) and the worst ideal solution (S^-) was calculated using formula (5) (Kacprzak, 2018):

$$\begin{cases} S_j^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_i^+\right)^2\right]^{0.5} \\ S_j^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_i^-\right)^2\right]^{0.5} \end{cases} \tag{5}$$

Table 6
Normalized weighted quality criteria values

Prototype	A1	A2	A3	A4	A5
P1	2.00	1.42	0.98	2.10	1.29
P2	2.00	1.62	1.93	1.59	1.76
P3	2.25	1.42	1.41	2.10	1.76
P4	1.65	1.82	1.84	1.59	1.29
P5	1.20	0.93	1.41	1.59	1.76
P6	1.60	1.62	1.75	2.10	1.29
V^+	2.25	0.93	0.98	1.59	1.76
V^-	1.20	1.82	1.93	2.10	1.29

where: as in Table 5

where: V^+ – the value of an ideal positive solution, V^- – the value of a perfect negative solution, i – criterion, j – prototype, $i, j = 1, 2, \ldots, n$.

Finally, the decision index – identical in this case to the quality indicator (O) of the paint prototypes – was calculated using formula (6) (Kaur et al., 2016):

$$O_j = \frac{S_j^-}{S_j^+ + S_j^-} \tag{6}$$

where: S^+ – ideal positive solution, S^- – ideal negative solution, j – prototype, $j = 1, 2, \ldots, n$.

The result is presented in Table 7.

Table 7
Quality indicator of paint prototypes

Prototype	S^+	S^-	O	Ranking
P1	0.88	1.30	0.60	2
P2	1.19	1.08	0.47	4
P3	0.83	1.32	0.62	1
P4	1.45	0.69	0.32	5
P5	1.13	1.24	0.52	3
P6	1.40	0.48	0.25	6

The analysis showed that prototype P3 was the most advantageous in terms of quality, best meeting customer expectations compared to the other evaluated products.

A life-cycle assessment of the water-based paints was then carried out. The selected environmental criterion was the carbon footprint, expressed in kilograms of carbon dioxide equivalent (Saif et al., 2015). Due to limited access to specialized data required for paint LCAs, the test study relied on literature data, specifically (Bertolini et al., 2020; Ronning et al., 1993). It was assumed that water-based paints emit 862±142 kg

CO_2 equivalent over their life cycle, considering total material flows, energy use, and all input and output resources. This emission corresponds to 1000 litres of product based on the "cradle-to-grave" LCA approach. Given that the prototypes were five-litre paints, the environmental burden was scaled down to 4.31 ± 0.71 kg CO_2 equivalent per unit. Based on these assumptions, the expert team estimated the CO_2 emissions for each paint prototype using their knowledge and experience. The results are shown in Table 8.

Table 8
Environmental index of paint prototypes

Prototype	*E*	Ranking
P1	3.97	2
P2	4.03	3
P3	3.60	1
P4	4.61	5
P5	5.02	6
P6	4.51	4

From an environmental perspective, prototype P3 was again predicted to be the most advantageous, having the lowest negative environmental impact in terms of CO_2 emissions. Notably, P3 also ranked first in terms of quality. However, this ranking may change when the cost aspect is considered. If P3 proves to be the most expensive option, the relative importance of quality, environment, and cost aspects must be weighed. If cost is not a limiting factor, a higher price would not preclude selecting P3 as the most beneficial choice. However, if customer purchasing tendencies favor low-cost options – evidenced by market research – cost may become the determining factor.

Accordingly, the production costs of the water-based paints were estimated using current market prices. This cost was simplified to reflect the price of purchasing a five-litre container. Based on this, a cost ranking was established under the assumption that lower cost is more favorable (Table 9).

Table 9
Price indicator of paint prototypes

Prototype	*K* (PLN)	Ranking
P1	140.00	5
P2	135.00	4
P3	160.00	6
P4	130.00	3
P5	115.00	2
P6	100.00	1

Prototype P6 was found to be the least expensive and, therefore, the most advantageous in terms of cost. Conversely, prototype P3 was estimated to be the most expensive. In the final stage, the obtained indicators were normalized using formula (1). Then, the aggregated QC-LCA indicator was calculated using formula (2). Based on this indicator, the final ranking of prototypes was developed (Table 10).

Table 10
QC-LCA indicator

Prototype	*O*	LCA	C	QC-LCA	Ranking
P1	0.94	0.74	0.33	0.67	1
P2	0.61	0.70	0.42	0.57	2
P3	1.00	1.00	0.00	0.67	1
P4	0.19	0.29	0.50	0.32	5
P5	0.74	0.00	0.75	0.50	3
P6	0.00	0.36	1.00	0.45	4

Two prototypes, P1 and P3, achieved the highest QC-LCA indicator value (0.67). It was concluded that these two prototypes most effectively balance the three pillars of sustainable development: quality, environmental impact, and cost. Therefore, they are expected to be best meet customer expectations, minimize environmental harm, and remain relatively affordable.

Under the test conditions of the procedure, it is recommended that the company pursue improvement actions aimed at developing products similar in characteristics to prototypes P1 or P3. However, if such development is not feasible, e.g. due to limited company resources – subsequent prototypes in the ranking, such as P2 or P5, may be considered. Prototype P4, identified as the least favorable, should be eliminated first, reducing the risk of resource waste.

Discussion

The popularisation of sustainable development has prompted companies to address the challenges they face. Efforts are being made to meet societal needs while simultaneously considering environmental and economic aspects. It has been observed that supporting approaches are emerging, particularly at the conceptualisation and prototyping stages. However, there is a lack of coherent techniques and concepts that enhance decision-making in product development while accounting for key aspects of product sustainability.

In this context, the objective was to develop a procedure to support decision-making related to sustainable product development, taking into account quality, environment impact, and cost. Based on this procedure, a ranking of product prototypes is created in terms of quality-environment-cost triad.

The procedure was tested and illustrated using water-based paints, evaluated through six different prototypes. Ultimately, two prototypes were identified as the most favourable in terms of meeting customer requirements, minimizing environmental impact, and optimizing costs. The key benefits of the proposed procedure include:

- Adapting product quality to customer expectations by considering various design alternatives.
- Enabling prospective assessment of environmental impacts at the early stages of product design.
- Predicting potential costs associated with planned project activities.
- Developing a ranking of product prototypes based on their alignment with quality, environmental, and cost aspects.

This procedure also offers business benefits, such as supporting product development at early stages, focusing activities on the most efficient options, and avoiding resource waste by eliminating the least beneficial solutions. Small and medium-sized enterprises (SMEs) with limited resources can use this procedure to evaluate quality, environmental impact, or costs with their own available techniques, potentially replacing more complex systems with low-cost alternatives.

Among the procedure's limitations are the need for reliable data for life cycle assessment, accurate cost modelling, and effective identification of customer requirements. Another limitation is the potential for expert assessment errors; however, it is assumed that experts are selected based on their relevant knowledge and experience in the research area.

Future research will explore other aspects of sustainable product development. Studies are planned within manufacturing companies to verify current practices that integrate quality, environment, and costs considerations during product design and improvement. Further research will also focus on cross-industry validation of the QLCA and CQ-LCA models, including additional case studies. There is also potential for simplifying the model using MCDM (Multi-Criteria Decision Making) to enhance its accessibility.

Conclusions

The growing necessity to protect the natural environment – combined with rapidly changing market requirements – makes sustainable action imperative. This remains a challenge, especially when trying to simultaneously address key aspects such as quality, environmental impact (via LCA), and costs.

Therefore, the objective was to develop a procedure based on the QC-LCA indicator to support decision-making during the early stages of product development. The procedure enables simultaneous analysis of various product prototypes in terms of quality (customer satisfaction), environmental impact (across the product life cycle), and cost. It is structured into five main stages: product selection and prototype development, quality assessment of product prototypes, life cycle assessment of product prototypes, cost assessment of product prototypes, and prediction of product development direction.

The procedure was demonstrated using water-based topcoat paints, which are commonly used for protective and decorative coatings in interior applications. Six prototypes were developed and evaluated based on five criteria: efficiency, total drying time, drying time between layers, number of layers to full coverage, and resistance to scrubbing. Based on the customer expectations, the quality indicator was determined for each prototype using the TOPSIS method. Prototype P3 emerged as the most advantageous in terms of quality. Subsequently, the environmental impact of the prototypes was estimated using life cycle assessment, with the carbon footprint serving as the key criterion. Again, prototype P3 proved to be the most environmentally friendly. Initial costs estimations indicated that prototype P6 would be the least expensive. Finally, the results were aggregated using the QC-LCA indicator. Taking quality, environment, and cost aspects into account simultaneously, prototypes P1 and P3 were identified as the most advantageous overall. As such, actions should be taken to improve and prioritize these prototypes.

The QC-LCA-based procedure is applicable to decision-making in the early stages of product development, including conceptualisation, prototyping, design, and improvement. It can be implemented in manufacturing companies striving to meet market demands, while addressing environmental concerns. This approach supports and enhances traditional design thinking by aligning it with the principles of sustainable development.

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