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FRAMEWORK FOR SELECTING QUALITY AND ENVIRONMENTAL ASPECTS IN THE QLCA METHOD SUPPORTING SUSTAINABLE PRODUCT DEVELOPMENT

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Purpose: The aim was to develop a framework for selecting quality and environmental aspects when improving products towards their sustainable development.
Design/methodology/approach: The framework was developed based on the results of previous studies, within which the Quality Life Cycle Assessment (QLCA) method was developed, dedicated to the sustainable development of products, taking into account the aspects of quality (customer satisfaction) and the environment (the impact of the product on the environment in the life cycle). During the development of the framework, a five-step methodology was used, i.e.: i) collecting data from previous studies, ii) computational simulation including verification of the proportions of the participation of aspects, iii) analysis and interpretation of results, and iv) development of a framework for the selection of aspects. The simulation was supported by the analysis of statistically significant differences in the Statistica 13.3 program with the ANOVA test.
Findings: If the quality indicator has a weight in the range of 0.70 to 0.35 and the environmental indicator of 0.30 to 0.65, then the quality and environmental aspects have a similar impact on the ranking. Then, it is possible to direct improvement activities to meet customer expectations regarding the quality of the product while limiting the negative impact on the environment of the product.
Research limitations/implications: The framework is primarily designed for use within the QLCA method. Additionally, it does not consider the proportion of other sustainability aspects, such as costs, which may affect product development decisions at later stages.
Practical implications: The framework is tailored to support designers' decisions in the early stages of product design and development. It can be used by manufacturing companies for sustainable product development as a tool to help predict product rankings depending on the adopted share of quality and environmental aspects.
Originality/value: To define new assumptions and concepts for product development in the form of a research framework that will support decision-making in guiding sustainable product development while taking into account quality (customer satisfaction) and environmental impact (LCA).

Keywords: QLCA, quality, life cycle assessment, customer expectations, production engineering, mechanical engineering.
Category of the paper: Research paper.

1. Introduction

Considering sustainability issues in process improvement and product development increasingly seems to be essential in successful enterprises (Berglund et al., 2020). One example of such action is the development and adaptation of current engineering practices and techniques to achieve effective ecodesign tools (Kobayashi et al., 2005). In this respect, quality management (QM) can provide significant benefits from the aforementioned integration, e.g. through continuous improvement and adaptation of products to customer requirements. As reported, e.g. (Gremyr et al., 2014), quality management is relatively well known, including integrated with management processes in most organisations, including often appropriately adapted to sustainable environmental activities.

Quality management can be understood as adapting a product to customer expectations, including ensuring their satisfaction with using the product, as in (Siwiec, Pacana, 2021; Pacana, Siwiec,2022b; Siwiec et al., 2023a). Quality management also involves minimising and eliminating product nonconformities as part of improving manufacturing processes, as in (Pacana, Siwiec, 2021, 2022a; Siwiec, Pacana, 2022). On the other hand, sustainable product development in its basic sense concerns achieving the quality of products that meet the expectations of society, including maintaining the principles of socially responsible products, limiting their negative impact and considering financial aspects (Bhasker, 2004; Siva et al., 2016a; Carvalho, 2017). Although these aspects are known and attempts have been made to integrate them, there is still a lack of principles and methods supporting the improvement of products towards their sustainable development.

In connection with this, a review of the literature on the subject in the field of sustainable product development was conducted, taking into account quality aspects. Among other things, the article (Arsic, 2016) analysed the possibility of presenting product quality in the form of actions carried out within the framework of sustainable development. The considerations and structure of the main quality aspects were analysed, including the synergy of the more important variables accompanying these undertakings. On the other hand, the authors of the study (Siva et al., 2016b) reviewed work in which quality management techniques were used together with other sustainable development initiatives. For example, integrated management systems, quality management within the implementation of management systems, integration of issues used in traditional work, or stakeholder management and customer orientation were selected. Similar studies were carried out by the authors of the work (Vandenbrande, 2021), in which a general framework was presented for small and medium-sized enterprises (SMEs) implementing sustainable development through quality management methods. As a result, a framework is proposed to support a qualitative economic and social system. On the other hand, the authors of the work (Güdemann, Münnich 2023), verified qualitative issues in terms of subjective choices of complex indicators used to measure sustainable development. The implications of missing data are carried out, including the creation of a research project in the form of the construction of a complex indicator that supports sustainable development. In turn, in the article (Jasiulewicz-Kaczmarek, 2014) an analysis of the impact of introducing sustainable development on quality management was carried out. Initiatives based on the prediction of possible changes in the organisation and the market were verified. Subsequently, the authors of the work (Wang et al., 2021) proposed a comprehensive model of decision-making within the framework of sustainable environmental management in the macroecological approach. The model was created in a mathematical approach in order to quantitatively consider complex factors influencing the policy of ecological environment management with the promotion of sustainable and balanced development. The framework of the modern concept of quality costs was also developed, which was considered in relation to all stages of the product life cycle, by all stakeholders in the supply chain, as, e.g., in (Tomov, Velkoska, 2022). Other works concerned the introduction of methods supporting the sustainable development of products towards a closed loop, such as by (Pacana et al., 2023). Furthermore, studies were conducted, e.g. (Tung, 2021), which analyzed the positive effects within the framework of quality management and achieving environmental sustainability, including sustainable development of the quality of these products. The issues of quality in industry 4.0 are also important in this respect, which can facilitate the improvement of products, but should also take into account environmental aspects, including the concepts of sustainable development. For example, as indicated by the authors of the works, among others (Stawiarska et al., 2021; Wolniak, 2021; Avilés-Sacoto et al., 2024).

It has been observed that improving the quality of products and at the same time reducing their negative environmental impact is used within the framework of the sustainable development approach. So far, the possibilities of integrating quality management and sustainable development have been considered, but no method has been sought to weight the aspects of sustainable development aspects in the product improvement process. Therefore, the objective was to develop a framework to select quality and environmental aspects during the improvement of products toward their sustainable development. This framework was developed based on the results of previous studies, for example (Pacana, Siwiec, 2024; Siwiec, Pacana, 2024b, 2024a, 2024c), within which the Quality Life Cycle Assessment (QLCA) method dedicated to sustainable product development was developed, taking into account the aforementioned quality and environmental aspects.

The developed framework can be used in manufacturing companies to focus the product improvement process to meet product quality and limiting their negative impact on LCA. Designers can determine the proportions of quality and environmental aspects in the early stages of product development so that they meet market expectations, as well as the individual requirements of the company using the indicated framework.

2. Problem and concept of research

The QLCA method is dedicated to designing and improving products as part of meeting customer expectations regarding product quality and at the same time ensuring their minimal negative impact on the environment in the life cycle (LCA). The QLCA method is based on the development of various product prototypes for which the voice of customers (VoC) is obtained (Shen et al., 2022). Based on customer requirements, the quality level of these prototypes is calculated, which is presented by the aforementioned quality indicator (Q). Subsequently, the environmental impact of prototypes is estimated according to the life cycle assessment method compliant with ISO 14040 (Finkbeiner et al., 2006). The results of the life-cycle assessment of prototypes are presented by the environmental indicator (LCA). These indicators are aggregated into one quality and environmental indicator (QLCA) according to which a ranking of prototypes is developed. On the basis of this ranking, product development decisions are made. The QLCA method is presented, e.g., in (Pacana, Siwiec 2024; Siwiec, Pacana, 2024b, 2024a, 2024c).

In the approach practised so far, the authors of the QLCA method assume that quality and environmental aspects are equivalent (equally important) to the decision maker, e.g. designer, manager, or experts in the field of quality management and environmental impact of products. This means that the quality of prototypes and their impact on the environment in the life cycle have the same share in the final decision regarding product development.

Based on previous studies in the field of quality and environmental improvement of products, e.g. (Pacana et al., 2023; Siwiec et al., 2023b) it was shown that manufacturing companies (mainly small and medium-sized enterprises, SMEs) (Lu et al., 2022) relatively often take into account qualitative aspects to a greater extent than environmental aspects when improving products. Therefore, it was considered reasonable to define a framework to select the proportion of the share of qualitative aspects in relation to environmental aspects in the QLCA method. This framework will be useful for entrepreneurs in the improvement activities they undertake, depending on market needs, but also being consistent with the idea of sustainable product development.

The research method was based on the development of a framework for the selection of quality and environmental aspects during the sustainable development of products according to the QLCA (Quality Life Cycle Assessment) method. The method was based mainly on computational simulation and sensitivity analysis carried out on the basis of a quality indicator (customer satisfaction with the use of the product) and an environmental indicator (product impact on the environment in the life cycle), which were developed according to the QLCA method presented, e.g., in (Pacana et al., 2023a). The adopted research scheme is presented in Figure 1.

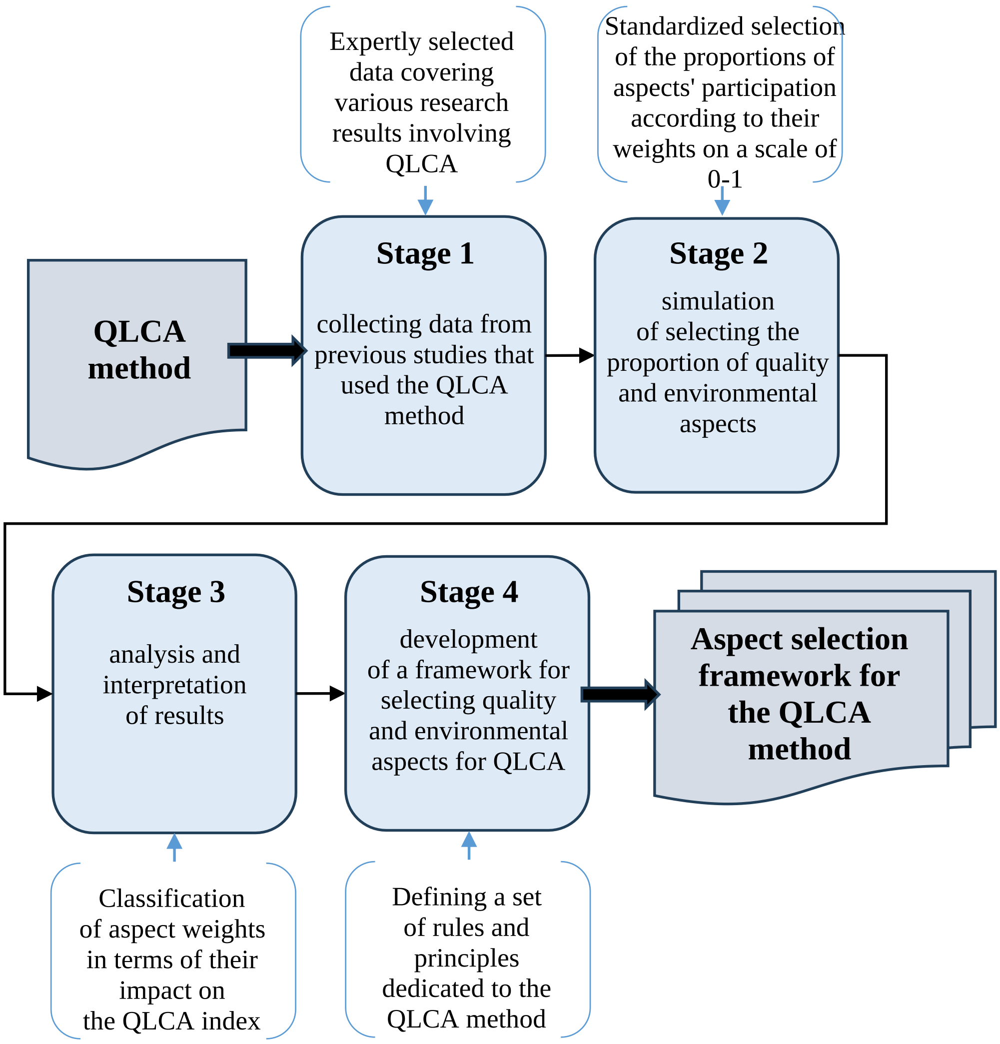

Figure 1. Scheme for developing a framework for selecting the proportions of quality and environmental aspects in the QLCA method.

Source: Own elaboration.

Therefore, the research method was developed in the following stages: i) collection of data from previous studies, ii) computational simulation based on the prediction of the selection of the proportions of the share of qualitative and environmental aspects, iii) analysis and interpretation of the results, and iv) development of a framework for the selection of aspects.

Obtaining data from previous studies refers to defining the data obtained during the use of the QLCA method. These data should include the values of the main indicators of the QLCA method, i.e. the Q indicator – qualitative and LCA – environmental. The indicators' values can be presented in any value (depending on the techniques used to support the implementation of the QLCA method, it is possible to obtain values from 0 to 1 or above 1). In the case of values above 1, these data should be normalized according to formula (1) (Pacana, Siwiec, 2024; Siwiec, Pacana, 2024a):

$$\begin{cases} \text{for } Q > 1: \dfrac{Q_{ij} - \min Q}{\max Q - \min Q} \\ \text{for } LCA > 1: \dfrac{\max LCA - LCA_{ij}}{\max LCA - \min LCA} \end{cases} \tag{1}$$

where:
Q – i-th value of the qualitative aspect,
LCA – i-th value of the environmental aspect,
j – product or prototype.

In turn, the computational simulation consists of assigning weights to these aspects on a scale (0-1), where these weights were changed by 0.05, which is justified by statistical assumptions about the detectability of statistically significant differences (Andrade, 2019). The weighted quality-environmental index was estimated as the arithmetic mean of the simulated weight and the value of the product of a given indicator, as presented in formula (2):

$$E_{ij} = \frac{w_{ij} \times Q_{ij} + w_{ij} \times LCA_{ij}}{2} \tag{2}$$

where:
w – i-th aspect weight (importance),
Q – value of the qualitative aspect,
LCA – value of the environmental aspect,
j – product or prototype.

During the simulation, weights equal to 0 and 1 are omitted. This results from the assumption of the QLCA method, where it is assumed that qualitative and environmental aspects are taken into account simultaneously without omitting any of them in the final result of the method.

Based on the simulation results, a comparative analysis is performed, and the results are interpreted. In this process, it is crucial to observe the change in the product prototype rankings (created according to the weighted quality or environmental indicator) in relation to the change in the proportion of indicators. On the basis of these observations, it is possible to develop a framework for the selection of quality and environmental aspects, the result of which is presented in the next chapter of the study.

3. Results

The framework for selecting qualitative and environmental aspects was based on data from previous studies by the authors, in which the QLCA method was used. It was based on data from a publication, i.e. (Siwiec, Pacana, 2024a), in which the QLCA method was applied to the sustainable development of photovoltaic panels. This product was modelled qualitatively and environmental way for thirteen prototypes. Based on customer requirements, a quality indicator was determined for the prototypes of this product, where the entropy method was used for this purpose. However, the life cycle assessment was carried out using the Ecoinvent database in the OpenLCA programme. Data on the values of the main indicators, i.e. Q – qualitative (customer satisfaction with the quality of the product) and LCA – environmental (impact on the natural environment of the product in its life cycle), developed as part of the research presented in (Siwiec, Pacana, 2024a), are presented in Table 1.

Table 1.
Results from the QLCA method presenting an equal proportion of quality and environmental indicators

Indicator	Pa	P1	P2	P3	P4	P5	P6	P7
Q	0.00	0.62	0.31	0.93	0.30	0.60	0.15	0.51
LCA	0.43	0.46	0.34	0.70	0.42	0.56	0.00	0.95
QLCA	0.22	0.54	0.33	0.82	0.36	0.58	0.08	0.73
Indicator	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	
Q	0.84	1.00	0.70	0.87	0.54	0.62	0.37	
LCA	1.00	0.60	0.34	0.39	0.51	0.39	0.25	
QLCA	0.92	0.80	0.52	0.63	0.53	0.51	0.31	

where: Q – quality indicator, LCA – environmental indicator, QLCA – quality-environmental indicator, Pa – current product, P1-P9 – prototypes.

Source: Own elaboration based on (Siwiec, Pacana, 2024a).

The data were expressed in the range of values from 0 to 1, therefore their normalization was omitted. Next, a simulation of the selection of the proportion of the share of qualitative and environmental aspects (expressed by the Q and LCA indicators) in the total quality-environmental index QLCA was performed. Formula (2) was used for this purpose. As a result, 19 simulations of the change in the weights of the aspects were performed, including taking into account the equivalent proportion of their share. The results are presented in Table 2.

Table 2.
Values of the simulated weighted quality index (Q) and weighted environmental index (LCA)

Q	LCA	Prototypes														
Proportion		**Pa**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**
0.95	0.05	0.01	0.31	0.16	0.46	0.15	0.30	0.07	0.27	0.42	0.49	0.34	0.42	0.27	0.30	0.18
0.90	0.10	0.02	0.30	0.16	0.45	0.16	0.30	0.07	0.28	0.43	0.48	0.33	0.41	0.27	0.30	0.18
0.85	0.15	0.03	0.30	0.16	0.45	0.16	0.30	0.06	0.29	0.43	0.47	0.32	0.40	0.27	0.29	0.18
0.80	0.20	0.04	0.29	0.16	0.44	0.16	0.30	0.06	0.30	0.44	0.46	0.31	0.39	0.27	0.29	0.17
0.75	0.25	0.05	0.29	0.16	0.44	0.17	0.30	0.06	0.31	0.44	0.45	0.31	0.38	0.27	0.28	0.17
0.70	0.30	0.06	0.29	0.16	0.43	0.17	0.29	0.05	0.32	0.44	0.44	0.30	0.36	0.27	0.28	0.17
0.65	0.35	0.08	0.28	0.16	0.42	0.17	0.29	0.05	0.33	0.45	0.43	0.29	0.35	0.26	0.27	0.16
0.60	0.40	0.09	0.28	0.16	0.42	0.17	0.29	0.05	0.34	0.45	0.42	0.28	0.34	0.26	0.26	0.16
0.55	0.45	0.10	0.27	0.16	0.41	0.18	0.29	0.04	0.35	0.46	0.41	0.27	0.33	0.26	0.26	0.16
0.50	0.50	0.11	0.27	0.16	0.41	0.18	0.29	0.04	0.37	0.46	0.40	0.26	0.32	0.26	0.25	0.16
0.45	0.55	0.12	0.27	0.16	0.40	0.18	0.29	0.03	0.38	0.46	0.39	0.25	0.30	0.26	0.25	0.15
0.40	0.60	0.13	0.26	0.16	0.40	0.19	0.29	0.03	0.39	0.47	0.38	0.24	0.29	0.26	0.24	0.15
0.35	0.65	0.14	0.26	0.16	0.39	0.19	0.29	0.03	0.40	0.47	0.37	0.23	0.28	0.26	0.24	0.15
0.30	0.70	0.15	0.25	0.17	0.38	0.19	0.29	0.02	0.41	0.48	0.36	0.22	0.27	0.26	0.23	0.14
0.25	0.75	0.16	0.25	0.17	0.38	0.20	0.29	0.02	0.42	0.48	0.35	0.22	0.26	0.26	0.22	0.14
0.20	0.80	0.17	0.25	0.17	0.37	0.20	0.28	0.02	0.43	0.48	0.34	0.21	0.24	0.26	0.22	0.14
0.15	0.85	0.18	0.24	0.17	0.37	0.20	0.28	0.01	0.44	0.49	0.33	0.20	0.23	0.26	0.21	0.13
0.10	0.90	0.19	0.24	0.17	0.36	0.20	0.28	0.01	0.45	0.49	0.32	0.19	0.22	0.26	0.21	0.13
0.05	0.95	0.20	0.23	0.17	0.36	0.21	0.28	0.00	0.46	0.50	0.31	0.18	0.21	0.26	0.20	0.13

Source: Own elaboration.

The ANOVA analysis was performed in Statistica 13.3. The aim was to check whether the obtained values of the weighted quality-environmental index differ statistically significantly between individual prototypes. This determines the validity of their further analysis. A test for factorial systems was used, i.e., independent variables, which were the values of the weighted quality-environmental index. As part of the analysis, a confidence interval of 0.95 and a significance level of 0.05 were established. The results of the analysis are presented in Table 3.

Table 3.
ANOVA test results

Test	Value	F	Df effect	Df error	P-value
Wilksa	0.231	60	1	18	0.000

Source: Own elaboration.

It was shown that there are statistically significant differences between the values of the weighted quality-environmental index obtained for product prototypes. This determines the validity of their further analysis. Therefore, the values obtained from the weighted quality-environmental index were compiled into prototype rankings. This is presented in Figure 2.

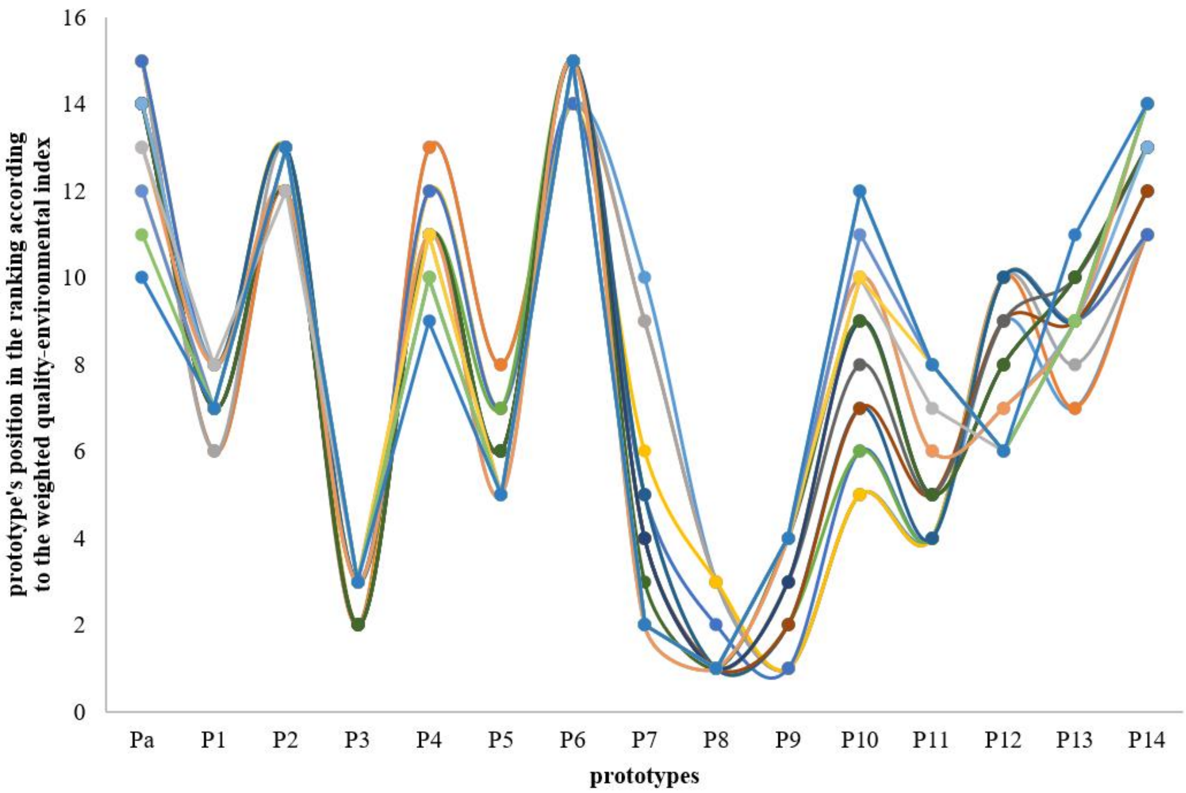

Figure 2. Changes in the prototype ranking according to changes in the proportion of quality and environmental aspects.

Source: Own elaboration.

It was observed that the importance of qualitative and environmental aspects generates changes in the position of prototypes in their final ranking, which is created according to the weighted qualitative and environmental index. Additionally, it was observed that:

- the higher the value of the quality indicator and the higher the weight of this indicator, the higher its position in the ranking;
- the low value of the qualitative and environmental indicators means that changes in the weights of these indicators do not significantly affect the prototype rankings;
- significantly high value of the quality indicator means that even if it is given a low weight, its position in the ranking changes relatively little;
- the higher the value of the environmental indicator and the higher the weight of this indicator, the higher its position in the ranking, only if the value of the quality indicator is relatively high compared to the others;
- if the value of the environmental indicator is low and its weight is high, including the value of the quality indicator being low or relatively unremarkable compared to the others, the prototype occupies a low position in the ranking.

The observations made it possible to demonstrate that the QLCA method is sensitive to prototype ranking taking into account the importance of quality and environmental aspects.

Table 4.
Framework for selecting the proportion of the share of quality and environmental indicators dedicated to the QLCA method within the framework of sustainable product development

Observation	The proportion of the indicator weights	Conclusion	Application
No change in ranking when: • the weighted value of the quality and environmental indicator is very low; • the weighted value of the quality indicator is very high and the environmental indicator is very low; Observed changes in ranking when: • the weighted value of the quality indicator is at an average level, and the environment indicator is very low.	Q ∈ ⟨0.95; 0.75⟩ LCA ∈ ⟨0.05; 0.25⟩	The quality index value generates a prototype ranking, while the environment index value has little influence on the ranking	Focusing improvement activities on meeting customer expectations regarding product quality, taking into account the basic aspects of impact on the natural environment
No change in ranking when: • the weighted value of the quality indicator is very low; • the weighted value of the environmental indicator is very high; Observed changes in ranking when: • the weighted value of the quality and environment indicator is relatively similar.	Q ∈ ⟨0.70; 0.35⟩ LCA ∈ ⟨0.30; 0.65⟩	The quality and environment index values have a similar impact on the ranking	Focusing improvement activities on meeting customer expectations regarding product quality while limiting the negative impact of the product on the environment
No change in ranking when: • the weighted value of the quality indicator is very low; • the weighted value of the environmental indicator is very high; Observed changes in ranking when: • the weighted value of the quality indicator is low and at the same time the weighted value of the environment indicator is at an average level.	Q ∈ ⟨0.30; 0.05⟩ LCA ∈ ⟨0.70; 0.95⟩	The value of the environment index generates the prototype ranking, while the value of the quality index has little influence on the ranking	Focusing improvement activities on reducing the negative environmental impact of the product, taking into account the basic customer expectations regarding product quality

Source: Own elaboration.

The proposed proportions of the share of the quality and environmental indicator are dedicated to sustainable product development in accordance with the QLCA method. Their selection may result from the specificity of the company's activity, including the concept of product development and market requirements.

4. Discussion and Summary

Enterprises take into account various criteria when making development decisions about products, services, technologies, or market position (Graham et al., 2005; Relich, 2023). In turn, promoting activities for sustainable development, it is necessary to take into account other key aspects, such as risk, time, or costs (Gonçalves et al., 2022; Ključnikov et al., 2022). Additionally, increased climate change generates the need to reduce the negative environmental impact of enterprise activities (Solaun, Cerdá, 2019; Serra et al., 2022). In the case of products that are an integral element ensuring the survival of manufacturing companies, including being a link between profits and customer satisfaction, it is necessary to assess their life cycle (LCA) (Schellscheidt et al., 2019; Lai et al., 2022). Therefore, it is necessary to search for methodological solutions that will support product development decisions, taking into account various aspects of sustainable development. In this study, the analysis focused on two selected aspects of product sustainability, which are key in the traditional approach to product improvement and maintaining environmental balance. These aspects are the quality of the product and its environmental impact on the environment in the life cycle (Garvin, 1984; Park et al., 2007; Gawlik et al., 2024). Therefore, the objective was to develop a framework for selecting quality and environmental aspects when improving products towards their sustainable development. This framework was developed based on the results of previous studies, for example (Pacana, Siwiec, 2024; Siwiec, Pacana, 2024b, 2024a, 2024c), within which the Quality Life Cycle Assessment (QLCA) method dedicated to sustainable product development was developed, taking into account the aforementioned quality and environmental aspects.

The framework supports the creation of product rankings taking into account the ratio of the share of meeting customer expectations and producing environmentally friendly products throughout their life cycle. Other, main benefits of the developed framework for selecting the proportion of the share of qualitative and environmental indicators include:

- improving the process of selecting quality and environmental aspects depending on the chosen product development direction,
- ensuring the appropriate dynamics of the participation of quality and environmental aspects in the product improvement process,
- verification of undertaken improvement actions in terms of quality and environment as part of the created product prototype rankings,
- support the decision-making process when predicting the direction of product development.

However, some limitations concern the omission of other important aspects of sustainable development, such as the costs of purchasing products. This may result in obtaining design solutions, including prototype rankings, which may change at later stages of development, e.g. due to the available budget. Additionally, the product selection framework is dedicated, in particular, within the QLCA method. This results from the adopted methodology, based on which the assumptions for creating the framework for selecting the proportions between the verified quality and environmental aspects were outlined.

Therefore, further research will include the extension of the QLCA method to other aspects of sustainable development. Then, it is planned to develop a framework for selecting the proportions of other aspects, e.g. cost. Another intention is to define a framework for selecting the proportions of sustainable development aspects that are general, which can be used not only within the QLCA method, but also within different approaches during the design and improvement of products.

Therefore, the developed framework for selecting quality and environmental aspects can be used by designers and experts during the development of sustainable products. Mainly, when using the QLCA method. The results will be useful when making development decisions, where it is crucial to direct actions towards achieving customer satisfaction with the quality of products and reducing their negative impact on the natural environment in the life cycle.

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