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FRAMEWORK OF QLCA MODEL CONSIDERING QUALITY AND LIFE CYCLE ASSESSMENT TO SUSTAINABLE PRODUCT DEVELOPMENT

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Purpose: The aim of the article was to develop a QLCA framework model dedicated to the design and improvement of products, taking into account their quality (Q) and environmental impact in the life cycle (LCA).
Design/methodology/approach: A review of the literature on the subject was conducted on studies from the Web of Science database. The thematic scope included the design and improvement of products, taking into account quality and environmental impact during the life cycle (LCA). Bibliometric and frequency techniques were used, including keyword analysis and citation of studies. Based on conclusions from the literature, approaches and methods for quality improvement, as well as the LCA methodology presented in the ISO 14040 standard, a QLCA framework model was developed. The model supports the prospective assessment of the quality and life cycle of the product and its prototypes in terms of sustainable development.
Findings: It has been shown that there are no solutions that present the links between product life cycle assessment and product quality assessment, including preparing these assessments for product prototypes at the design and prototyping stage.
Research limitations/implications: A QLCA framework model is presented, the proper form of which will be provided by future research. The framework conditions of the QLCA model were improved and expanded in order to find the most advantageous approach to achieving the highest quality product quality with the lowest possible negative environmental impact of this product in LCA in terms of its sustainable development.
Practical implications: The QLCA framework model is the result of conceptual generalisation, and its assumptions were prepared for designers and R&D departments. The assumptions of the QLCA methodology can be used by management staff to make decisions about product improvement at the prototyping stage.
Originality/value: A novelty is the QLCA framework model, which presents an original approach to product improvement at the prototyping stage, taking into account customer expectations regarding their quality and at the same time assessing the life cycle of these prototypes.

Keywords: quality, LCA, product improvement, sustainable development, production engineering, mechanical engineering.
Category of the paper: conceptual paper.

1. Introduction

Climate change and global warming cause companies to try to limit the negative impact of their activities on the environment (Barecka et al., 2016; Pacana, Siwiec, 2024). In recent years, solutions supporting the sustainable development of products have been increasingly sought (Kimpimäki et al., 2022; Pacana et al., 2023a). As part of these activities, it is effective to strive to meet customer expectations, achieve environmentally friendly and economically beneficial production (Siva et al., 2016). Although the indicated aspects often function well separately, it is still problematic to take them into account simultaneously in the product improvement process.

Obtaining and processing customer requirements is one of the essential activities during product development. Voice of the customer (VoC) (Shen et al., 2022) is the basis for decisions made regarding product planning already in the early stages of its development (Siwiec, Pacana, 2021). Based on precisely defined customer requirements, it is possible to design new products, but also to improve products already present on the market (Zhou et al., 2023). The process of obtaining and processing customer requirements is well known and popular and is also used in practice. Among other things, surveys (Ponto, 2015), questionnaires, interviews (Wang, Liu et al., 2023), and the Kansei method (Yamagishi et al., 2018) are used to obtain customer requirements. However, the processing of customer requirements can be done via the popular QFD method (Quality Function Development) (Haiyun et al., 2021; Siwiec et al., 2023), where customer needs are translated into technical criteria, or the Kano model (Neira-Rodado et al., 2020), or e.g. the FAHP method (Fuzzy Analytic Hierarchy Process) (Chan, Kumar, 2007), which is used to reduce subjectivity and increase precision in the requirements specified by customers. Product quality improvement activities are usually focused on key quality criteria, i.e., the most important for customers and having a significant impact on customer satisfaction with the use of the product (Kim, Oh, 2001; Sever, 2015). To predict customer satisfaction levels, it is useful to offer product prototypes to customers. Based on those that are most beneficial to customers, it is possible to select a prototype suitable for production by the company (Wang, Ranscombe et al., 2023). This is a complex process and is carried out on principles different from the process of assessing the environmental impact of a product. Therefore, it is difficult to combine these aspects into one coherent approach to product improvement. In the case of environmental product assessment, one of the main methods is life cycle assessment (LCA) (Chevalier, Le Téno, 1996). Most often, it takes place according to the „cradle-to-grave" approach, i.e. taking into account the phases of extraction and processing of

materials, production, use, and end of life (EoF) (Proske, Finkbeiner, 2020). Conditions for life cycle assessment are included in the ISO 14040 standard, where it is beneficial to perform LCA for known products and processes. This is due to the LCA methodology, which depends on many criteria, including: selection of the environmental load criterion according to which the life cycle assessment is carried out, time limits and place of analysis, functional unit supporting the standardization of data, and, above all, input and output data (Grenz et al., 2023; Karaman Öztaş, 2018; Proske, Finkbeiner, 2020). Therefore, if these criteria are not recognised properly, limited access to reliable and detailed data may lead to erroneous results. This context is not conducive to conducting LCA in the early stages of product development, including that it does not appear to be effective when evaluating prototypes (Wu, Su, 2021). Therefore, this is one of the key areas that poses problems when prospectively assessing the quality of product prototypes and combining it with the life cycle assessment. From the point of view of sustainable product development, this action is necessary; therefore, it is reasonable to look for solutions supporting the process of integrating activities to meet customer requirements (quality) with eliminating the negative environmental impact in the product life cycle (LCA) (Gajdzik et al., 2024). The review of the literature on the subject indicates that the area of research on product improvement from a quality-environmental perspective, i.e. including simultaneously taking into account customer requirements for product quality and assessing the product life cycle, is not popular and is in an early stage of development.

Therefore, the aim of the article was to develop a QLCA framework model dedicated to the design and improvement of products, taking into account their quality and environmental impact during the life cycle (LCA). The developed model can be used by designers, managers and decision-makers of manufacturing companies to design products and build requirements for their sustainable development at this stage.

2. Literature Review

A review of the literature on the subject was conducted, which included the design and improvement of products taking into account quality and environmental impact during the life cycle (LCA). The literature review was conducted in June 2024. Studies from the Web of Science (WoS) database were analysed. The method for identifying studies in this database is presented in Table 1.

Table 1
Method of selecting studies for content analysis

Analysis criterion	Results
Criterion (in title, abstract and keywords)	„life cycle assessment" and „quality"
Time range	from 1989 to 2023
Number of all identified studies	3212
Restriction: open access studies	1439
Studies consistent with the analyzed research area	35

Source: Own study based on Web of Science database.

The studies were searched according to the entries in the title, abstract, and keywords, i.e. life cycle assessment and quality. The studies were identified in the time range automatically generated in the WoS database, i.e., from 1989 to 2023. As a result, 3212 studies were obtained. As part of their standardised analysis, the scope of study was limited to those with open access. There were 1439 of them. All identified studies were subjected to preliminary analysis according to the abstract. Ultimately, 35 studies were obtained that corresponded to the given research topic. Then, these studies were subjected to bibliometric and frequency analysis. Supported by computer programmes: Gephi 0.10 and VOSviewer 1.6.20.

Initially, the type of study was analysed. 25 scientific articles were selected, followed by 7 conference articles and 2 reviews of the literature. This proves the universality of the research topic as a subject of utilitarian and practical research.

Then, the number of studies published per year in a given time range was analysed. The aim was to determine the pace of development of the analysed research area, as shown in Figure 1.

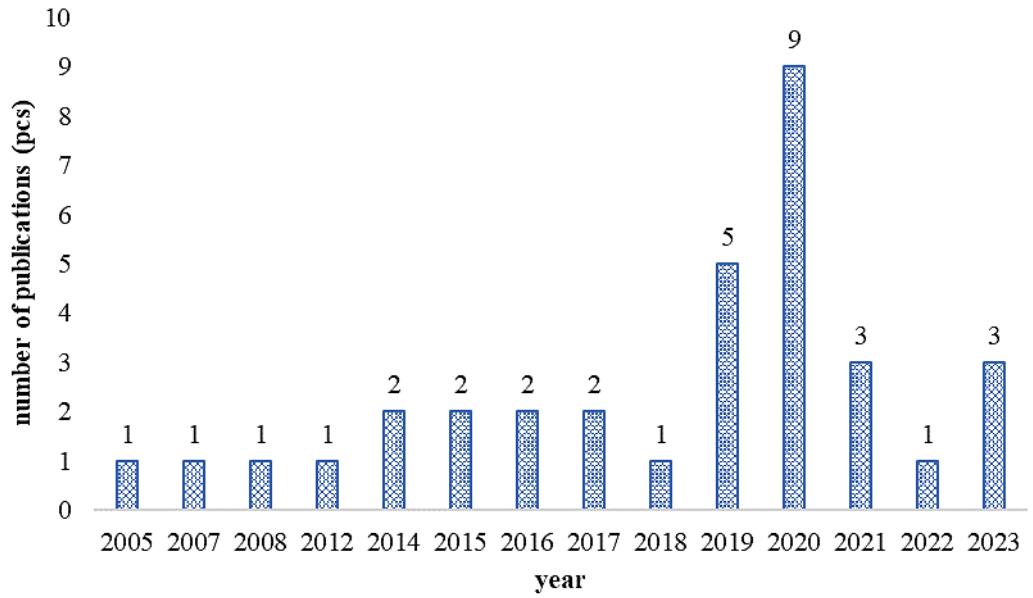

Figure 1. Number of published studies per year.

Source: Own study based on Web of Science database.

It was observed that the first study corresponding to the selected research area was published in 2005, and in subsequent years, e.g., until 2018, the number of publications included no more than two studies per year. An increase in the number of publications occurred in the period 2019-2020, but in the following years there is a decrease in the number of publications, where in the entire selected time range of 2005-2023 the number of publications is negligible. Therefore, it was concluded that the research area under study is in the initial phase of development and is characterised by research gaps. For this reason, it is worth investigating and requires further research in the analysed area.

Subsequently, the keywords of the studies indicated by the authors and entered in the WoS database were analysed. Keyword verification began with quantitative and then qualitative analysis. The number of occurrences of given keywords was initially verified and additionally, as part of a standardised analysis, keywords were grouped according to their acronyms. Table 2 shows the keywords that occur most frequently (up to five repetitions).

Table 2
Keyword frequency

Keywords	Number of occurrences
LCA (and: life cycle assessment, life-cycle assessment, life cycle analysis)	20
QFD (and Quality Function Development)	7
FRAMEWORK	6
DESIGN	5
IMPACT	5

There were 292 total identified keywords. The most frequently occurring word is "life cycle assessment" and its acronyms (20 occurrences). However, the occurrence of this word results from the "entry" entered when searching for studies in the WoS database. Then, the word "QFD" (including its extension, i.e. Quality Function Development) appeared very often (7). The words "framework" (6), "design" (5) and impact (5) appeared frequently. This means that the research area regarding product quality and assessment of its environmental impact in LCA is in the development phase, where its framework is being created and quality is manifested in the form of product design. The cloud of all keywords is shown in Figure 2.

Figure 2. Keyword cloud.

Source: Own study based on Web of Science database.

The larger the font size of a keyword, the more frequently it appeared. In the analysed case, the keywords specified in all verified studies were taken into account. The number of occurrences of repeated words was negligible.

The number of citations to the studies selected for analysis was then analyzed. The number of citations was determined in June 2024 based on all citations from the WoS database. Of all the analysed publications, the most frequently cited were:

- study (Rosen, Kishawy, 2012), which concerned the characteristics of sustainable production and the role of environmental development, as well as green production and LCA in the process of improving production processes - number of citations 242;
- study (Sakao, 2007), which presented a method supporting product design taking into account quality and environmental aspects, which integrated techniques such as: LCA (life cycle assessment), QFDE (implementation of quality functions for the environment), and TRIZ (theory of solving inventive problems) - number of citations 147;
- study (Kobayashi et al., 2005), presenting a method for quantifying eco-efficiency using the QFD method and the LCIA method – number of citations 47.

The studies most frequently cited are considered crucial from the point of view of the development of the analysed research area. They can be considered as a basis for further research by other authors. The indicated studies concern the basics of product design taking

into account customer expectations, e.g. via the QFD method. They also indicate opportunities for environmental improvement based on the results from the LCA method.

Then, mutual citations (according to references) of the studies selected for analysis were analysed. This was done on the basis of the bibliographic items included in each of the studies selected for verification. The aim was to determine the coherence and degree of development of the analysed research area. The result is shown in Figure 3.

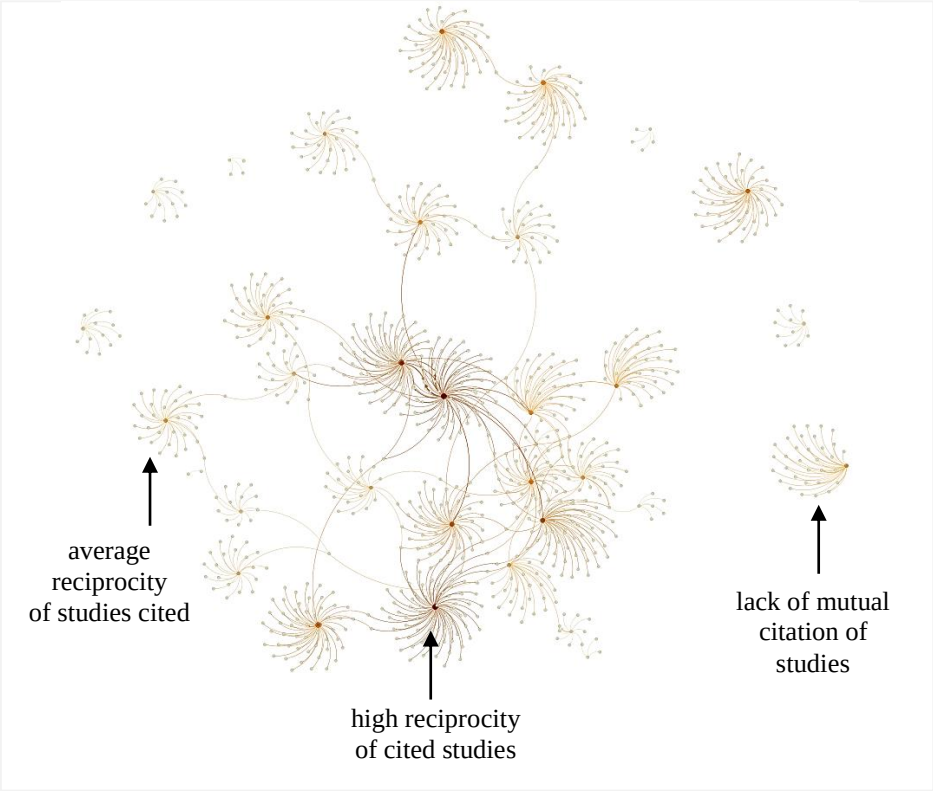

Figure 3. Mutual citation of studies.

Source: Own study with using Gephi 0.10.

The analysis of the mutual citation of the studies showed that there is little consistency in the citations of the studies selected for verification. Only a few studies have been observed that have a mutual relationship, but it is negligible. The selected research area was again shown to be in the initial stage of development, which confirms the need to undertake research in this area.

Based on the results of the bibliometric analysis, the adequacy of the selected studies in relation to the adopted research topic was confirmed. Therefore, these studies were subjected to content analysis. Table 3 presents a synthetic summary of the review of the content of the studies.

Table 3.
Synthetic list of studies according to the main thematic scope.

Study	Thematic scope
(Adriyanti, Sahroni, 2023; Cabot et al., 2019; Grant et al., 2015; Haber, Fargnoli, 2021; Han et al., 2021; Kaķis et al., 2020; Kobayashi et al., 2005; Kulatunga et al., 2015; Mrozik, Merkisz-Guranowska, 2020; Neramballi et al., 2020; Pacana et al., 2023b; Popoff, Millet, 2017; Puglieri et al., 2020; Sakao, 2007; Segovia et al., 2019; Ulewicz et al., 2023; Vigil et al., 2020; Yu et al., 2014)	Product quality & environmental impact in the product life cycle
(Antony et al., 2016; Berglund et al., 2020; Hameed et al., 2022; Katsiropoulos, Pantelakis, 2020; Kulczycka, Smol, 2016; Lewandowska et al., 2017; Palousis et al., 2008; Romli et al., 2015)	Product quality & environmental impact over the product life cycle & cost
(Alvarenga et al., 2019; Dassisti et al., 2019; Filleti et al., 2014; Pagone et al., 2020; Piasecka et al., 2020; Rosen, Kishawy, 2012; Shahbazi et al., 2019)	Sustainable development of products in terms of improving their production processes

Source: Own study.

The area of research in the field of product design and improvement has been shown to be classified into three main thematic areas:

1. Product quality and environmental impact in the product life cycle.
2. Product quality, product environmental impact on LCA, and product cost.
3. Sustainable product development in terms of improving production processes.

So far, the largest number of studies have been thematically focused on improving product quality and life cycle assessment. Another direction of research also includes costs and the orientation of production processes toward sustainable development.

The review of the literature on the subject indicates that the area of research on product improvement from a quality-environmental perspective, i.e. including simultaneously taking into account customer requirements for product quality and assessing the product life cycle, is not popular and is in an early stage of development.

3. Conceptual framework model

Based on the review of the literature on the subject, it was observed that the scientific problem that motivates the presented research is the lack of solutions that present the links between product life cycle assessment and the product quality assessment, including assessing product prototypes at the design and prototyping stage. Therefore, the life cycle assessment (LCA) method into the process of improving product quality, taking into account customer expectations. Therefore, this study presents the framework of the QLCA model (Q – Quality, LCA – Life Cycle Assessment) for prospective assessment of the quality of product prototypes and assessment of their environmental impact throughout the life cycle. The idea of developing a QLCA model is to support the process of predicting a prototype that is the most advantageous in terms of quality and at the same time has the lowest possible negative environmental impact in the life cycle.

In line with the current approach to product development, it is crucial to acquire the voice of customers (VoC) so that the offered products are satisfactory to them. This approach is well known and is still popularised. However, in the era of sustainable product development, it seems to be insufficient. This is due to increased climate change and the increase in greenhouse gases, but also to the growing awareness of customers and the environment to make well-thought-out purchasing decisions. They should focus not only on the high quality of the product but also on the need to care for the natural environment. A popular and considered key method for assessing environmental impact in this regard is the LCA method. It is mainly used in the case of known products (already on the market) where the necessary data is available for a reliable assessment of environmental burdens resulting from the product life cycle. However, it is difficult to use the LCA method at the early stages of product development, especially in the case of prototyping various production alternatives depending on both quality and environmental criteria.

In the assumptions for the developed framework of the QLCA method, it is assumed that the evaluation of product prototypes is carried out in a multidimensional manner, taking into account an integrated approach to reducing the negative environmental impact during the product life cycle and improving product quality, taking into account customer requirements. Then, it is possible to develop a production solution that will be satisfactory to customers (e.g. a high-quality, innovative product that meets the requirements for its use) and has a limited environmental impact. Supporting decision making in the early stages of product development helps reduce resource waste, and the general nature of the QLCA method is consistent with the principles of sustainable product development, where not quantity but quality matters.

The constructs of the QLCA framework model are adopted in the form of ecological policies of the European Union and Poland, in which the "life cycle thinking" approach is applied there. Sustainable development of products, including environmentally friendly production processes, is increasingly becoming a fundamental activity of enterprises, e.g. within the Integrated Product Policy, climate policy, and the Paris Agreement. The LCA method is indicated in many EU and national documents as the basic method for life cycle assessment, where it appeared in Poland, among others: in the Act on Environmental Protection Law (2001; Journal of Laws No. 62, item 627). Other documents that support the development of the framework of the QLCA model include, for example, the Environmental Product Declaration (EPD), EMAS, ISO 14001, or standards from the ISO 14040 group, as activities supporting environmental protection, but also the QFD method or the ISO 9001 standard, in nature of activities related to product quality. The QLCA concept is based on the indicated standards and techniques, including the marking and use of product and customer information. The novelty of the offered approach is the skilful selection of instruments (principles, methods, and tools), including the methodology of standardised and systematic prospective assessment of the quality and environmental load of product prototypes as early development. The framework conditions of the QLCA method are presented in Figure 4.

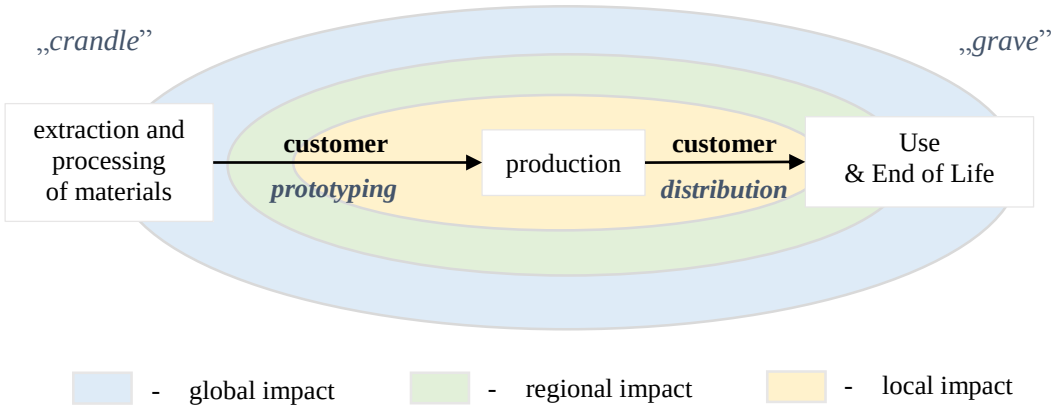

Figure 4. Framework conditions for QLCA.

Source: Own study.

It is assumed that the QLCA model is based on the „cradle-to-grave” concept, i.e. it takes into account the phases: extraction and processing of materials, production, use, and end of life. These may be supplemented by distribution and transport. Additionally, according to the ISO 14042 standard, the following are considered mandatory: (1) defining the purpose and scope of the research, (2) establishing inventory data, (3) life cycle assessment, (4) interpreting the results. As part of the QLCA model, it is necessary to establish the functional unit (normalising the results) and system boundaries, e.g. regarding time and place in relation to conducting LCA.

As part of the QLCA model concept, the prototyping process in these phases, taking into account the customer's requirements for product quality. It is assumed that it will precede the production stage, where the direction of product development is determined. In the QLCA model, this is done by establishing prototypes of an existing product (on sale). The product and its prototypes are characterised by main quality criteria (affecting customer satisfaction with its use). These criteria are subject to customer evaluation, where the quality of the criteria for individual prototypes is assessed, including the importance of these criteria for customers. The acquired customer requirements are processed to determine the quality index (Q) that represents the level of customer satisfaction with the offered prototypes. The results regarding the quality of the prototypes are integrated with the results of evaluating the environmental impact of the prototypes during their life cycle. The process of integrating the results of a life cycle assessment (LCA) with the results of a qualitative assessment (Q) begins with conducting a life cycle assessment of the current product (on sale). Then, the environmental load result in LCA for the current product is modelled depending on the offered product prototypes, which are distinguished by other quality criteria parameters (taken into account in the quality assessment). The implementation diagram of the prototype quality assessment process in the life cycle assessment (LCA) process is presented in Figure 5.

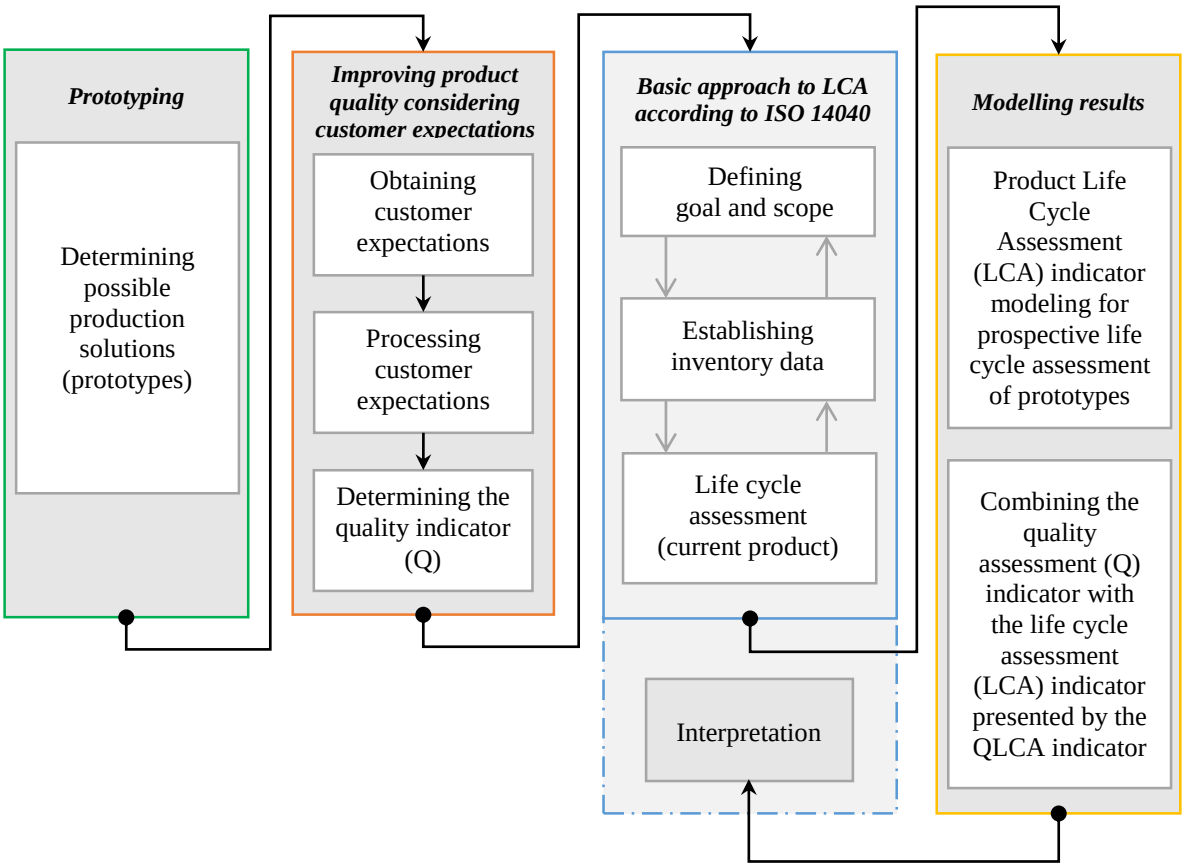

Figure 5. Scheme of implementing the process of assessing the quality of prototypes in the process of assessing their environmental impact during the life cycle.

Source: Own study.

Initially, it is assumed that product prototypes will be developed on the current product. These prototypes are evaluated by customers. The results of customer evaluations (regarding satisfaction with the prototype criteria and the importance of these criteria) are processed to determine the quality index (Q). After reviewing the literature on the subject, it is possible to support this process with other techniques, e.g. survey, questionnaire, interview - to obtain customer requirements, and the QFD method - to transform customer requirements into technical requirements. Subsequently, individual stages are undertaken within the LCA methodology according to the ISO 14040 standard. The LCA results concern a reference product (current, on sale) and include a selected environmental load criterion selected depending on the needs and nature of the product. This is followed by modelling with the reference product life cycle assessment (LCA) indicator, which covers the prospective life cycle assessment of product prototypes. This modelling is done taking into account the offered quality changes. At the final stage, the results are interpreted, i.e. final conclusions are formulated from the analysis, including determining the direction of product development in accordance with the QLCA results.

The QLCA framework requires the development of a methodology to evaluate a product according to quality and environmental criteria. In the case of environmental assessment, it is possible to support this process with available computer programmes, e.g. OpenLCA. Currently, the popularisation of the QLCA model is limited due to the lack of information and available solutions indicating a coherent and hybrid quality-environmental analysis in terms of combined quality assessment and life cycle. The framework conditions of the QLCA model were improved and expanded in order to find the most advantageous approach to achieving the highest quality product quality with the lowest possible negative environmental impact of this product in LCA in terms of its sustainable development.

The prepared framework model is the result of conceptual generalisation and its assumptions were prepared for designers and R&D departments. The assumptions of the QLCA methodology can be used by management staff to make decisions about product improvement at the prototyping stage.

4. Discussion and conclusion

The developed QLCA framework model was created based on a gap that concerns the lack of a methodology that supports the product improvement process while taking into account quality and environmental criteria in the context of the product life cycle. The authors are aware that the framework of the QLCA model should be expanded to include further criteria supporting the sustainable development process, e.g. costs, which will determine the final development decisions. The results of the QLCA model can support designers and managers in making decisions regarding the design of products to meet customer requirements (quality) and, at the same time, product designs will be properly interpreted in terms of their life cycle environmental impact (LCA). The concept of the QLCA model allows planning the production of a product in advance, which is carried out as part of a prospective quality and environmental assessment of prototypes. Therefore, companies can produce a competitive product in advance.

Therefore, the concept of the QLCA model assumes product development in the perspective of sustainable development, which is primarily focused on taking actions and decisions in the design stage. The QLCA model is used to identify critical areas and product criteria that absolutely need to be improved. In addition, the results of the QLCA model can help determine the direction of improvement activities that can be adapted to the company's production capabilities. Developing a general QLCA model may be useful in systematic and standardized product development, including comparing undertaken activities with the quality and environmental requirements of other enterprises (benchmarking).

The expected advantages of the QLCA model include:

- taking into account environmental burdens in the life cycle of the product and its prototypes in the form of a "cradle to grave" approach that allows for a comprehensive assessment of the product;
- ensuring customer participation in the product improvement process;
- the possibility of using the results of the QLCA model to apply for certification, e.g., ISO 14001 or ISO 9001, which promotes continuous product improvement and company development.

The advantages of the QLCA model are also expected to encourage companies to make greater efforts to protect the natural environment, while at the same time ensuring customer requirements by offering them various environmentally friendly production solutions with the expected quality. According to research conducted in Polish consumers (Gajdzik et al., 2023), consumption in Poland changed in recent decades. After the economic transformation in Poland, consumers' awareness has been shaped. In the market economy, quality and sustainability are very important for them. Quality in sustainable products is constantly evolving as customers' tastes and tastes change. In the concept of Industry 4. 0 and strong support of modern technologies, the customer can realize his dreams in the designed product (Saniuk et al., 2020). Thus, the proposed framework of the QLCA model can be used to verify the designed products in order to ensure, on the one hand, that they are quality consistent with customers' expectations and, on the other hand, that they are sustainable.

As part of future research, the authors plan to develop a universal QLCA model that will be applicable to any type of product commonly used by customers. At the same time, it is planned to continuously improve the concept of the QLCA model framework and adapt it to market changes, including the principles of sustainable development, e.g. by taking into account production costs.

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