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Open eco-innovations in sustainable product development: Model framework of design thinking in quality life cycle assessment (DT-QLCA)

Dominika Siwiec^{a,1} , Bożena Gajdzik^{b,2} , Remigiusz Gawlik^{c,3} , Radosław Wolniak^{d,*,4} , Andrzej Pacana^{a,5}

^a Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Rzeszow 35-959, Poland

^b Faculty of Materials Engineering, Department of Industrial Informatics, Silesian University of Technology, Poland

^c Krakow University of Economics, College of Public Economy and Administration, Department of Public Management, and North-West University, NWU Business School, South Africa

^d Faculty of Organization and Management, Silesian University of Technology, Gliwice 44-100, Poland

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ABSTRACT

Sustainable product development requires integrating eco- and open innovation. Traditional Design Thinking (DT), while effective for iterative product improvement, often lacks the capability to address environmental considerations comprehensively, necessitating new approaches to balance consumer needs with ecological stewardship. Despite growing attention to sustainability, existing methodologies fail to integrate consumer-focused innovation with systematic environmental responsibility. We tried to bridge this research gap by combining DT with Quality Life Cycle Assessment (QLCA) model to support eco-innovation within sustainable product design. This study aims to answer two research questions: 1) How can DT be integrated with QLCA to support open innovations in sustainable product development? 2) How can the DT-QLCA framework enhance decision-making processes in product design to align sustainability goals with customer expectations? Its objective is to develop a holistic framework that facilitates sustainable innovation while maintaining market competitiveness. An interdisciplinary DT-QLCA framework, integrating quality and sustainability metrics into the early stages of product development was developed. DT-QLCA bridges DT and environmental assessment, creating a structured decision-making tool that supports resource optimization, reduced environmental impact, and enhanced customer satisfaction. It can be applied in manufacturing industry for product designing and production management, bringing also added value for the environment and society.

1. Introduction

Reducing the negative environmental impacts is a challenge for countries worldwide. Environmental issues arising from the consumption of products and services continue to outweigh efforts in regenerating, processing, and recycling ecosystems (Go et al., 2016; Huong et al., 2021; Meidute-Kavaliauskiene et al., 2021; Yun et al., 2023). Due to the increasingly serious environmental problems caused by product consumption, consumers are being encouraged to change their

consumption behaviours toward more sustainable practices (Gong et al., 2022; Gajdzik et al., 2023). Optimizing production, consumption, and product recycling can be achieved through sustainable design thinking (DT). Creativity among employees is necessary in sustainable design thinking to foster innovation (Gajdzik and Wolniak, 2022a; Yang et al., 2022).

From this perspective, open innovation plays a vital role in promoting collaboration at the organizational level, consumers, and other external stakeholders for the generation of new ideas and solutions

* Corresponding author.

E-mail addresses: d.siwiec@prz.edu.pl (D. Siwiec), bozena.gajdzik@polsl.pl (B. Gajdzik), remigiusz.gawlik@uek.krakow.pl (R. Gawlik), rwolniak@polsl.pl (R. Wolniak), app@prz.edu.pl (A. Pacana).

¹ ORCID: 0000-0002-6663-6621

² ORCID: 0000-0002-0408-1691

³ ORCID: 0000-0003-3934-2131

⁴ ORCID: 0000-0003-0317-9811

⁵ ORCID: 0000-0003-1121-6352

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relative to sustainability practices (Dabić et al., 2023). In addition, it enables firms to enhance sustainable design processes by leveraging various perspectives and expertise emanating from various domains, which culminates in newer, more innovative, and effective means of reducing environmental impacts (Al Nuaimi et al., 2024; Carrasco-Carvajal et al., 2023; Costa et al., 2023; McGuckin et al., 2022;). Through open innovation, there will also be increased sharing of knowledge and resources that will amplify an organization's development of best sustainability practices towards the rapid creation of eco-friendly products (Giardino et al., 2023). In this respect, such a collaborative approach will spur innovation while being focused on consumers who are increasingly informed and keen to act responsibly in the way they consume a product (Chu and Liu, 2023; Oliveira and Rua, 2024; Romero-Rodríguez et al., 2020). This will be an important lever in view of the transition toward a more sustainable economy.

Design thinking is considered a research-oriented approach to analysing problems, relying on creative thought processes (Matthews et al., 2019). It is primarily applied in the product domain (Micheli et al., 2019). It involves a systematic search for solutions and is often showcased in research and development (R&D) activities and product innovations (Schraven et al., 2023). In the concept of Industry 4.0, the innovations are strongly linked to the capabilities of technologies, known as the pillars of Industry 4.0. Companies are implementing solutions that bring them closer to smart manufacturing, and the scopes of change are subject to measurement in maturity models (Radziwon and Vanhaverbeke, 2024; Gajdzik, 2022; Gajdzik et al., 2025).

In sustainable business strategies, the DT concept in product improvement is based on accurate identification of a product's environmental problem at an early stage of product design, so that the product meets customer needs. DT requires an LCA approach 'from cradle to grave' (Liedtka, 2014). The main benefits of using DT supported by LCA include reducing potential decision-making errors in product development (Liedtka and Kaplan, 2019; Rösch et al., 2023) and promoting a culture within the organization that highlights product eco-innovations (Elsbach and Stigliani, 2018; Yun et al., 2020; Vinichenko et al., 2021).

Although design thinking is implemented in companies (Micheli et al., 2019), there is still a lack of widespread acceptance of methodologies that present a standardized procedure for sustainable product development (Beverland et al., 2015; Chen and Venkatesh, 2013). This was identified as a research gap that this study aimed to address. Based on a literature review and the authors' ongoing research, it was observed that the design thinking approach, enhanced by the QLCA (Quality Life Cycle Assessment) method (Gajdzik et al., 2024), could contribute to supporting the product design and improvement process. DT-QLCA combines DT with a prospective quality assessment of product prototypes and their life cycle environmental impact analysis.

Also, in open innovation and sustainable product development, there is a need for research regarding the absence of standardized frameworks that integrate open innovation practices with structured methodologies such as QLCA and design thinking (Marullo et al., 2024). While open innovation emphasizes collaboration on the flow of ideas and knowledge between the internal and external sources, it has still to be effectively linked to design methodologies able to comprehensively assess environmental impact (Carrasco-Carvajal et al., 2023). That is an important difference, since most current product development frameworks currently focus, in a bipolar extremes of either customer-centered innovation or sustainability alone, rather than their integration into an approach that could tie environmental considerations in a product life cycle with the active incorporation of diverse external insights.

Most of the existing models about sustainable product development lack capturing mechanisms for the contributions of stakeholders, including customers and environmental experts, in an iterative and structured way (Cirule and Uvarova, 2022; Kiseleva et al., 2022; Lee and Roh, 2023). Hence, companies are not able to adopt a cohesive approach to eco-innovation by carrying out the principled way of open

innovation. This therefore makes the DT-QLCA framework proposed in this paper unique in offering a model that would, indeed, effectively enable the integration of environmental assessments within an open innovation-driven design process. In this sense, the actual gap in the academic and practical study of such integrated frameworks has consequences: it diminishes the companies' ability to create sustainable products responsive to the market's needs and responsible environmental stewardship.

In this paper, the new model was described. In this model, LCA was linked to DT and Q (quality). Design thinking in QLCA (Quality Life Cycle Assessment) was proposed (DT-QLCA).

DT-QLCA allows to create product prototypes based on customers' expectations (Q) and their environmental impact in product's life cycle (LCA). The process involves searching for eco-innovative product solutions and their sustainable development. Product prototypes are created in the conceptual phase based on the product currently in sale. The prototypes are parametrized by quality criteria, impacting customer satisfaction when using the product. This is done in a multidimensional and multi-criteria form, supported by MCDM techniques. Hence, the quality criteria are shown in current and modified forms/states, where their actual form is as the same as in the product currently in sale. Modified prototypes are future possible products. Exemplary forms/states of criteria are weight, color, or length. Then, the criteria are assessed by customers, e.g. in survey research. Based on these assessments, the quality level of each prototype is calculated as the Q indicator. Then, prototypes are assessed for their environmental impact, according to the environmental burden criterion in LCA - following ISO 14040 standards. Next, the environmental impact indicator is obtained - the LCA indicator. Then, Q and LCA indicators are integrated to the Quality Life Cycle Assessment indicator - the QLCA. QLCA helps creating rankings of prototypes to select the best solutions in sustainable development, i.e. prototypes which have the highest quality and simultaneously the lowest negative environmental impact throughout their life cycle. The set of tools and approaches used in QLCA model are integrated with traditional DT process, which is discussed in detail later in the article.

Therefore, it can be said that this paper shall focus mainly on the proposition and development of a unified framework that incorporates DT with QLCA for the furtherance of sustainable product development through eco-innovation. More precisely, the developed framework will be referred to as DT-QLCA, where the aim is to develop environmentally friendly products while also satisfying consumer needs. The model therefore provides a structured approach to sustainable design by integrating customer-focused innovation with life cycle-based environmental assessment in the development of products designed with minimal ecological impact and maximum user satisfaction.

This will address the significant gap that exists in the current methodologies on sustainable product design, which are usually lacking in systematically embedding environmental impact assessment within customer-centered innovation processes. It was shown, that the traditional DT approach is an iterative process that is mainly based on the voice of the customer (VoC). However, the dynamics of market changes and the need to protect the environment force more complex, multi-criteria decisions based not only on VoC, but also on environmental or cost criteria. This corresponds to the approach to sustainable product development. Despite this, product development towards sustainability is still in the development phase, including the lack of methods and models that would support decision-makers at the early stages of product creation (conceptualization). Additionally, creating new or heavily modified products involves the process of open innovation, which in this respect seems to be inevitable. This holistic approach requires an appropriate research framework, and due to the fact that traditional design thinking is not yet adapted to changes towards sustainable products and open innovation, this was considered a research gap that was assumed to be filled.

The paper discusses a framework that allows embedding

sustainability considerations right from ideation to prototyping and testing, thus opening up a new avenue for organizations in reducing their environmental footprint. It also points out that open innovation splits the integration of insights from external stakeholders in enhancing the sustainable value of product design.

This model will contribute not only to ecological and economic benefits for companies but also to enhanced capabilities to respond to the continuous evolution of market demands linked to sustainable products.

On the basis of the literature analysis (a brief literature review), we have specified the two research questions (RQs):

RQ1: How can design thinking be integrated with Quality Life Cycle Assessment (QLCA) to support the implementation of open innovations in sustainable product development?

RQ2: How can the DT-QLCA framework enhance decision-making processes in product design to align with both sustainability goals and customer expectations?

The motivation for this research is the fact, that DT can be employed to enhance the process of product design and improvement. Despite various modifications of DT, we were not able to find a complex DT methodology for sustainable product development. This gap was filled by our proposal of a new framework for Design Thinking in Quality Life Cycle Assessment (DT-QLCA). The novelty of DT-QLCA approach is the modification of our own Quality Life Cycle Assessment (QLCA) model to include open innovation in sustainable product solutions through DT procedure.

The paper presents an original framework model DT-QLCA for the stage of eco-innovation in product design. The approach, in the form of model framework, lies in utilizing existing concepts and methodologies of design thinking for sustainable product development at the stage of designing new products that meet customer expectations while being environmentally friendly throughout their life cycle. The application of DT in QLCA for product sustainability differentiates the model from traditional product design and prototyping approaches and methodologies. The proposed model contributes to product improvement and the pursuit of innovations in sustainable product development. Inclusion of open innovation in the DT-QLCA framework further amplifies the latter's effectiveness by collaborating with various stakeholders, such as consumers, suppliers, and research institutions. This allows for an interactive environment in generating ideas and pooling insight into new opportunities related to eco-innovation. Where organizations involve external contributions in the process of design, they stand to gain from a larger knowledge pool and expertise that may lead to the development of more innovative and sustainable products. Open innovation certainly accelerates development related to environmental friendliness and aligns product design with the emerging and changing consumer expectations who stand increasingly on sustainability grounds (Yun et al., 2022, 2023; Vignieri, 2021). Finally, integrating open innovation into the DT-QLCA model reinforces a holistic approach toward sustainable product development by fostering both ecological and economic benefits.

Practical application of the DT-QLCA model framework can take place in manufacturing companies, mainly in teams of designers, managers and environmental experts. The DT-QLCA model promotes and deepens sustainable design thinking among practitioners and researchers, offering a multidisciplinary, methodical approach to reducing the environmental impact of products while striving to meet customer demands. Managers and other decision-makers can drive product eco-innovation by applying the proposed DT-QLCA model.

The DT-QLCA model brings together cross-functional teams that involve designers, managers, and environmental experts, and external actors to participate in collaborative ideation sessions. In this way, diverse knowledge will be put to work and build creative ideas that satisfy customers while meeting sustainability objectives (Gajdzik and Wolniak, 2022b). Innovation can be inspired by cooperation with external agents: suppliers, consumers, and research institutions. These

external partners will apply the DT-QLCA model for structured workshops and co-creation sessions, hence offering insight and expertise that will help arrive at more sustainable product designs. The model can be used at the level of process improvement in Industry 4.0 conditions in the following areas of influence of projects on the enterprises' operations: productivity, agility and speed, quality, competitiveness and enterprise value, profitability, staff reduction, delivery improvements, vertical and horizontal integration, resource savings, reduction of operating costs, technology adaptability and quality of machine operations. (Gajdzik and Wolniak, 2022c).

The DT-QLCA model can, therefore, be applied to establish continuous feedback loops with customers and stakeholders. In this respect, the involvement of their contributions along the whole design phase allows firms to make sure that the products developed are appealing for market demands and sustainability goals. Iterative design is supported for rapid prototyping and testing of new ideas. It may further mean, in an open-innovative approach, a collaboration with external innovators or startups in order to explore new solutions and accelerate the development of eco-innovative products.

The DT-QLCA model framework supports both economic and ecological growth. A key factor in this process is the generation of diverse design solutions during the early stages of development - primarily during concept creation and prototyping. These solutions are analyzed with a focus on quality (aligned with customer requirements) and their environmental impact throughout the life cycle. The design outputs (prototypes) are developed either as entirely new eco-innovative solutions or as significantly modified products. As a result, the selected prototypes are expected to meet market demands while being environmentally sustainable across their life cycle.

Companies adopting DT-QLCA will benefit from a streamlined design process, supported by specialized tools. The quantitative approach to measuring quality and environmental impact minimizes subjectivity and enhances decision-making precision. Based on DT-QLCA results, companies can accurately predict the outcomes of design decisions in terms of customer satisfaction and environmental protection, both of which contribute to financial profitability. This methodology also reduces resource waste commonly associated with traditional design approaches. By adopting DT-QLCA, organizations can dynamically respond to market changes, aligning their actions with the principles of sustainable development.

All prior studies addressing the research gap and other relevant aspects are discussed in Section 2, which includes the theoretical foundation of integrating DT with QLCA and a literature review on the DT role in sustainable product development.

2. Theoretical background

2.1. Approach to design thinking

Design thinking is a method for developing innovative solutions to complex problems by analysing the concerns, interests, and values of people in the design process (Bender-Salazar, 2023). According to this approach, design is iterative, allowing for the development and testing of multiple design solutions to select the most advantageous one. As stated by Li et al. (2019), design thinking is based on five main characteristics: (1) a human-centred focus, (2) integration of real and hypothetical solution scenarios, (3) collaboration of interdisciplinary teams, (4) a holistic approach to the problem, and (5) a distinctive staged process of action. The design thinking process is framed in five main stages (Rösch et al., 2023). In accordance with the proposed concept, the design thinking process was extended to include an approach to idea evaluation using MCDM (Multi-Criteria Decision-Making). To this methodology, DT-QLCA was added as an enrichment component, as shown in Fig 1. Our proposed DT-QLCA methodology (a model framework) is an integral part of the MCDM.

The initial stages involve observation and analysis of the situation

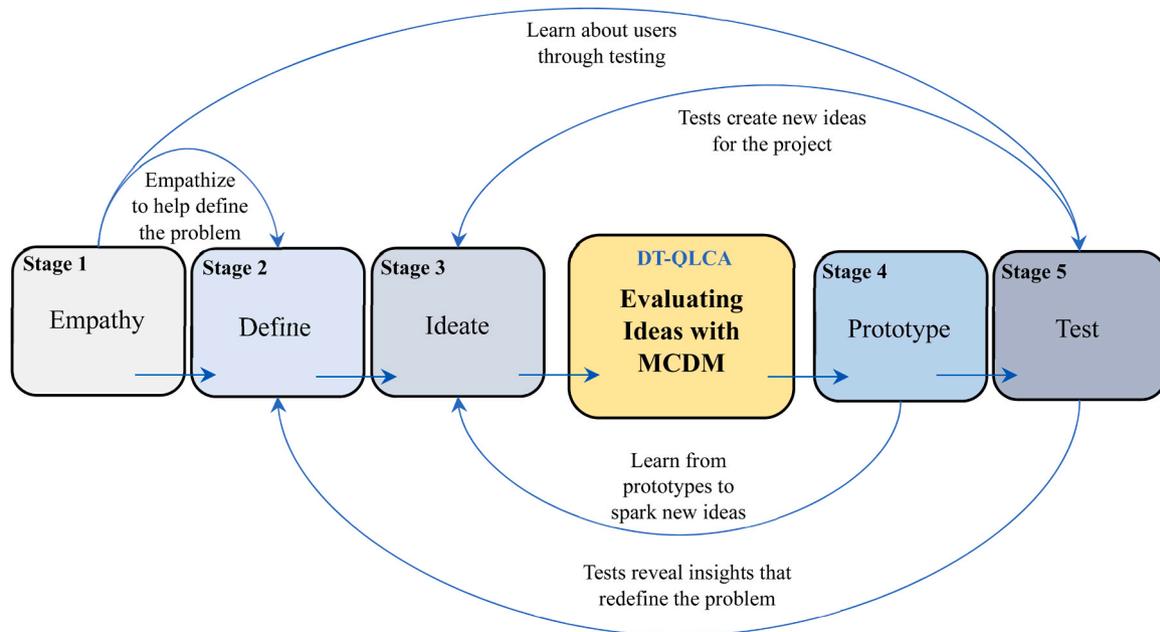


Fig. 1. Five-stage nonlinear design thinking process with DT-QLCA. Own elaboration based on (Li et al., 2019).

(problem), particularly considering customer requirements. This entails understanding customer needs, hence the term empathy, which includes recognizing hidden expectations, such as sensations, emotions, motives, and others (Nagaraj et al., 2020). Additionally, the design thinking approach aims for a comprehensive understanding (definition) of the analysed problem, considering other factors such as the environment, trends, and resources. Analysing the full decision-making situation, breaking it down into interpretations of the various connections and patterns present, stems from systems thinking. Common tools used in these initial stages include market observations, customer interviews, and customer behaviour mapping (Rösch et al., 2023). Furthermore, active engagement of customers in the co-creation process is necessary (Luotola et al., 2017), which is particularly evident in the concept of Industry 4.0 and the accompanying technology of product personalization (Saniuk et al., 2020).

This integration of LCA with customer interviews appears to be a promising approach and will help in finding solutions to all the contradictions related to eco-innovation. The challenge, however, is represented by stakeholder engagement, especially when iterative and interactive processes are foreseen, as in those described in the DT-QLCA framework. First, of course, there are hurdles: differences in priority between the stakeholders, limitations of resources, and issues that are difficult to handle regarding how to get comprehensive and useful feedback. Artificial Intelligence can play an important role in mitigating those challenges, hence facilitating the integration process for an efficient pathway to eco-innovation (Wang, 2024).

It allows for involvement by systematically allowing improved data collection and analysis in customer interviews and LCA. For example, NLP algorithms can also provide transcription of the data, analysis and synthesis of customers' interactions, identification of key themes, sentiment, and emerging concerns. This ensures that the Voice of Customer is systematically captured at each and every touchpoint (Vital et al., 2024). On top of that, AI-powered tools could contribute to the creation of dynamic empathy maps and personas from ongoing input, making stakeholders' insights more actionable in the design process (Mehdipour, 2024). In this context of LCA, AI algorithms make the environmental impact assessment more efficient and precise. AI integrated within the LCA methodologies may, therefore, help the firms automate their data collection processes from diverse sources, model the

environmental burdens under various scenarios, and simulate the probable results of different kinds of product designs. It also identifies predictive analytics on long-term sustainability issues that might crop up due to product innovation. This again is in close confluence with the DT-QLCA framework, wherein all the quality and environmental impacts are studied concurrently along the product life cycle (Berthelot et al., 2024).

AI contributes to stakeholder engagement way beyond the analysis of data: facilitating collaboration in open innovation eco-systems is one. Intelligent matchmaking systems will highlight external contributors relevant to the issue at hand—for instance, environmental experts or suppliers—on the basis of their knowledge and experience. AI-powered platforms can support ideation workshops in the co-creation process by pre-generating suggestions, incorporating brainstorming sessions, and ensuring that different participant inputs are constantly integrated within a coherent design process (Lamnatou et al., 2024). The other contribution of AI is overcoming languages and communication gaps among the stakeholders around the globe. AI-powered, real-time translation tools will enable interaction by teams and all other collaborators with ease and hence assure the inclusion of ideas. AI chatbots or virtual assistants have also been used to engage customers in continuous feedback loops, thus facilitating iterative design and testing phases of DT-QLCA (Yaghoubi and Kumru, 2024).

AI could also be instrumental in enhancing visualization tools and simulations. AI-enhanced design software can create detailed prototypes and simulations of product designs, thereby allowing stakeholders to see what the implications of different choices could be. Such tools make difficult-to-understand environmental and technical data more accessible and, hence, support better decision-making by all participants (Vital et al., 2024). AI can address resource constraints that are typically associated with stakeholder engagement. This will include automated scheduling, facilitation of meetings, and follow-up communications that reduce the administrative burden entailed in the coordination of diverse groups so that stakeholder engagement is consistent throughout the project life cycle. These efficiencies allow more agile applications of the DT-QLCA model. Secondly, AI makes stakeholder engagement scalable. For example, sentiment analysis or feedback aggregation tools leverage large pools of data contributed by stakeholders—such as surveys or online forums—so that the diversity of opinion can actually be considered rather

than swamped by volume (Tabrizi et al., 2023). In the larger context of open innovation, both eco-innovation and design thinking can be strongly enhanced. Open Innovation advocates for faster development of new products and services by use of external and internal ideas and paths to market (Appleyard and Velazquez, 2024). By integrating open innovation into eco-innovation, companies can reach a wider circle of knowledge, ideas, and expertise from outside partners, research institutions, startups, and even the public. This approach opens up a collaborative environment that is more inclusive and diverse in problem-solving, where solutions are not confined to the internal capabilities of one organization but are co-created with a broader set of stakeholders (Plugmann, 2024).

Design thinking in open innovation enhances the power of collaboration in problem-solving by putting an even greater emphasis on human-centered design and empathy. It lets organizations collaborate with independent innovators, communities, and users to create sustainable solutions fitted to the particular needs and contexts of a place (Bartar, 2023). Open innovation enables the cross-industry and cross-sector sharing of ideas and practices that accelerate the development of solutions that may well have never been realized in a closed innovation process. In many cases, this results in new ways of approaching sustainability challenges that take into consideration not only technological but also social, economic, and cultural dimensions, making the innovations holistic and scalable (Wilson et al., 2023; Fabrizio et al., 2023).

This integration of eco-innovation and design thinking in open innovation processes opens up opportunities for organizations to rethink their approach at a systemic level. It promotes a circular economy model where resources are reused, repurposed, and regenerated rather than being used up and discarded. It allows stakeholders to surpass the traditional linear production and consumption processes in their effort to seek ways of creating value that would benefit both the environment and society. By using open innovation to source ideas, technologies, and business models from diverse sources, organizations may create more sustainable and scalable solutions that accelerate the transition towards a more sustainable global economy (De Waters and Kotla, 2023; Meinel and Krohn, 2022).

The convergence of eco-innovation, design thinking, and open innovation forms a forceful framework through which environmental issues today and tomorrow can be effectively addressed. At the crossroads of creativity, collaboration, and sustainability, new solutions that meet the current short-term environmental challenges but also lay down the foundation for the future in a sustainable manner are created (Beaudoin et al., 2022; Kim et al., 2024; Roh et al., 2023). Such would be an acknowledgement that no organization, or one single entity, can solve some very daunting problems facing the planet alone. Rather, if the actors unite to share relevant knowledge and also develop inclusive innovations, impactful change affecting both man and the planet may result (Goncalves et al., 2024; Sarango-Lalangui et al., 2023).

The subsequent stages involve idea generation, which in the practice of design thinking consists of developing hypotheses regarding the previously defined problem and preliminary prototyping. Processing the accumulated data aims to define specific patterns of innovation (Liedtka, 2020). The creativity of design teams and effective collaboration among experts belonging to interdisciplinary teams is particularly important, as it can be a key success factor in this process (Halvorsen, 2013; Gajdzik and Wolniak, 2022b). Expert teams should generate as many divergent ideas as possible, which should then be narrowed down to those that are most feasible or consistent with the adopted design idea (Rösch et al., 2023). Utilizing discussions and brainstorming, as well as visualizing prototypes and mapping product values, is helpful (Seidel and Fixson, 2013).

In the product testing stage based on their prototypes, tests, experiments, and other solutions are employed. Testing occurs within repeated and modified experiments to find the most optimal solution possible (Nakata, 2020). It is essential to adopt a learning-by-doing approach.

Prototyping in design thinking involves creating a product in the conceptual phase, with minimal resources, solely to obtain feedback that is used for subsequent combinations of design solutions (Liedtka, 2014; Rösch et al., 2023). At this stage, the best solutions are identified according to the product characteristics defined within the company. As stated by Elsbach & Stigliani (2018), testing aims to obtain feedback on three dimensions: attractiveness to customers, feasibility in technical terms, and business profitability. Popular supporting techniques include creating small tangible models or conducting field research with external stakeholders (Rösch et al., 2023). DT also employs ethnographic methods, personas, journey maps, brainstorming, mind maps, visualizations, and experiments (Micheli et al., 2019).

Based on the literature review related to the methodology of DT, the following conclusions were formulated:

- The application of DT at the stage of seeking innovative design solutions helps designers analyse problems in a more comprehensive and logical way, allowing for the development of a clear strategy for product improvement;
- The focus of DT on identifying new or significantly modified products includes perceptual analyses, which, to be effective, should be methodologically standardized;
- DT must align with the principles of sustainable product development, but this is not easy due to the complexity of product structures and the breadth of environmental requirements (Geissdoerfer et al., 2016);
- DT requires the involvement of many employees, designers, managers, and external stakeholders (Bocken et al., 2014, 2015);
- DT must be flexible and should be modified and expanded according to market needs (Boons et al., 2013) and the requirements of sustainable product development.
- DT creates an environment for creativity and experimentation, suggesting to teams the option of processing farfetched ideas and solutions that might result in a breakthrough (Gajdzik and Wolniak, 2022a).
- DT fosters open innovation since, with the practice, internal teams can work together with external partners and integrate a number of views and a set of expertise that might be useful for the innovation process (Loderer and Kock, 2021; Alaniz-Munoz et al., 2023; Hawryszkiewicz and Alqahtani, 2020).
- DT pays great attention to quality in design processes so that the product can answer user needs but also meet high standards of functionality, usability, and sustainability for greater customer satisfaction and success in the long run (Carhuacuma and Ovalle, 2023).

2.2. Literature review of design thinking in sustainable product development

A synthetic literature review was conducted on the applicability of design thinking to the search for new (innovative) product solutions in the context of their sustainable development. The review was based on works identified in the Web of Science (WoS) database in September 2024. These were open access works that were searched using the terms 'design thinking' and 'sustainable development' in the title, and abstract, and keywords. A total of 984 papers were obtained. 21 papers were selected for content analysis, and these papers were in line with the adopted thematic area. Selection of works corresponding to the adopted research topic was made according to narrative selection based on the authors' expert knowledge.

It was observed that attempts were made to develop frameworks for design thinking in the context of sustainable product development, both through testing their capabilities (e.g., Castiblanco Jimenez et al., 2021) and by exploring opportunities for digital production development in the context of Industry 4.0 (Ching et al., 2022; Soomro et al., 2021), as well as verifying the prototyping of handicrafts (Li et al., 2019). It was

noted that a frequently analysed criterion of sustainability within design thinking was society, as seen in (Diepenmaat et al., 2020; Hoolohan and Browne, 2020; Maher et al., 2018; Matthews et al., 2019), where efforts were made to develop coherent approaches, interactive tools, and frameworks that support the principle of responsible research and innovative product solutions. These studies were primarily focused on creating new value and reducing costs for society. The review of these papers confirmed that design thinking has particular applicability in addressing complex social problems related to technical, organizational, and political issues. Connections integrating design thinking were sought within these issues to create conceptual frameworks that assist in dealing with complex social problems, as presented in (da Costa Junior et al., 2019).

There were also studies involving the development of business model frameworks for creating sustainable value while considering sustainability criteria (Ferlito and Faraci, 2022; Geissdoerfer et al., 2016; Kozłowski et al., 2016; Santa-Maria et al., 2022) and models supporting sustainable innovations in the supply chain, such as (Nilsson and Göransson, 2021), where design thinking was integrated for creating innovations in the supply chain, taking into account strategies, practices, culture, and the political context of enterprises. The holistic approaches presented in these works include analyses of the methods and evolution of design towards increasing sustainable development in the supply chain, including products, innovative business models, and consumption. By extending this approach beyond the supply chain, including customer expectations, it is possible to support sustainable production and consumption, including the development of business models (Kozłowski et al., 2016; Pyykkö et al., 2021). The possibilities of modeling design thinking in relation to innovative strategic management were also examined (Bonini and Sbragia, 2011). It was confirmed that design thinking models require improvement in terms of the approach to processes and the corporate culture in which they are applied. Despite some shortcomings, it is considered effective due to its ability to support its functioning with appropriate techniques that enable understanding of the context, including generating ideas that take customer requirements into account.

Also, design thinking was applied for sustainable development by creating opportunities for resource productivity growth (Birkeland, 2022; Dewberry and de Barros, 2009). The studies cited as examples included eco-innovative products. Strategies, structures, systems, processes, and outcomes of the company were redesigned. The main goal was to highlight the potential for exploring connections between human capital and environmental impact (socio-ecological development) to foster innovation in the context of sustainable development. Eco-innovations involving green product design implemented according to design thinking (also interpreted in this case as green design thinking) were presented by Batwara et al. (2022). In their work, techniques were proposed to support the creation of eco-innovative product solutions, including the Kano model for identifying and processing customer expectations, as well as the FAHP (Fuzzy Analytic Hierarchy Process) method for determining the ranking of customer requirements and supporting the production process of eco-friendly products. In a similar vein to the search for sustainable design thinking, research was conducted by Yang et al. (2022). Their work includes an analysis of sustainable consumption practices. The analysis they performed contains aspects (criteria) for evaluating designers.

LCA is a methodological framework that characterizes the environmental impacts associated with a product, process, or service from extraction of raw materials to final disposal. A full overview runs right from resource use, energy consumption, and emissions, among other environmental aspects related to the product or service. This gives LCA the opportunity to point out, while assessing those very impacts, those critical stages in a life cycle that could be optimized by reducing adverse environmental outcomes (Bajdur, 2021).

In the wider sense, eco-innovations include all new products, processes, services, and business models contributing to reducing

environmental burdens and thus contributing to sustainable development. Generally, eco-innovation has been inspired by increasing awareness and consciousness due to emerging challenges people face, and this is supposed to contribute toward the preservation of natural resources and reduction of ecological footprints. Eco-innovation in nature is all about value creation, which does not merely relate to economic profit but also makes contributions to environmental and social positivism (Sala, 2020).

They cross on meeting LCA and Eco-innovation points for the very reason that is to ascertain sustainability. Precisely speaking, LCA has been drawing very vital data or insight into environmental impacts of existing system hence showing where innovation has high demand. The potential of LCA is to be used by eco-innovators as a tool that would enable them to assess the overall environmental advantages of new technologies, products, or processes while their innovations are not only economically viable but also superior from an environmental point of view compared to the existing ones (Renaud et al., 2024; Bałazińska et al., 2020).

Integration of LCA into the process of eco-innovation helps avoid unintended negative consequences of new technologies. That is, such eco-innovations at one stage of the life cycle do not simply shift the environmental burden to another stage while overall environmental impacts are reduced. The very reason is the importance of taking new technologies-in instances like electric vehicles or renewable energy systems-forward in such a way that their usually complex environmental footprint is well managed by means of LCA (Taelman et al., 2019; Petit-Boix et al., 2018).

The relevance of the junction between LCA and eco-innovation is particularly relevant in today's world, considering that the global economy increasingly orients towards sustainable directions. There is widespread awareness in the minds of policymakers, businesses, and research institutions for the need of tools and approaches guiding solution development to meet market demands while contributing to solving key global sustainability challenges. LCA integrated into the process of eco-innovation would support organizations in making informed decisions for the circular economy: using resources with high efficiency, waste at a minimum, and the environmental burden as low as possible. The synergy between LCA and eco-innovation is a basic driver to support the evolution of technologies and practices that go on advancing environmental stewardship by guaranteeing economic development, as well as social progress concurrently (Renaud et al., 2024).

Whereas LCA offers an overall, information-based method of considering environmental impacts in either a product or process, eco-innovation concerns the formulation of solutions aimed at lowering or totally avoiding those impacts. LCA can, moreover, provide certain indications regarding key areas where the eco-innovation could have major environmental contributions to ensure sustainability during its entire life cycle. Innovations themselves are driven by goals on sustainability. LCA will be able to guide the design process by providing insight into which stages of the product life cycle need most improvement and where environmental impacts can be minimized. In return, innovations can be designed with sustainability as a key criterion, which aligns with the LCA framework (Bajdur, 2021; Taelman, 2020).

Following the introduction of an eco-innovation, LCA may report back on whether reached outcomes match the proposed environment objective and in what ways constant fulfilment of the promises from the innovation by environmental betterment were met along the life cycle of the innovation. These concepts can be converged together in influencing policy and regulation and allow sound, scientific evidence about environmental benefit of eco-innovations to be supplied. LCA data can be used by governments to develop incentives or regulations that encourage the development and diffusion of eco-innovations.

By connecting open innovation with design thinking, both make use of collaboration and the incorporation of users (Loderer and Kock, 2021). Knowledge derived from open innovation-that is, engaging

external stakeholders could help the design thinking process to better align solutions. In contrast, design thinking may reinforce open innovation by the systematic gathering of user feedback and iteration of ideas with the intent of making innovations novel yet answering precisely to user needs (Alaniz-Munoz et al., 2023). This interplay of the two approaches creates an enabling environment that can allow organizations to make use of diverse perspectives and expertise for more innovative and effective solutions. Conjoining open innovation with design thinking, thus, may set organizations better to react and at the same time create value in a challenging, ever-changing environment (Alqahtani, 2020).

A summary of the main observations from the literature review is presented in Table 2.

It was concluded that design thinking has the characteristics of an approach aligned with sustainable product development; however, there is a lack of established frameworks for designing eco-innovations in sustainable product development while simultaneously meeting customer requirements. This was recognized as a research gap, which the authors aimed to fill by incorporating DT in QLCA called DT-QLCA.

Eco-innovations represent a transformative approach to product development that integrates environmental considerations into the innovation process (Liu et al., 2024). In this context, design thinking emerges as a powerful methodology that complements and enhances the implementation of eco-innovations. Design thinking emphasizes empathy, creativity, and iterative problem-solving, which are essential in addressing the complex challenges associated with sustainability (Wang and Huang, 2024). The importance of eco-innovations lies in the need to understand and address the environmental impacts of products throughout their entire lifecycle (Dilip and Kerr, 2024). Design thinking facilitates this by encouraging teams to engage deeply with users and stakeholders, allowing for a better understanding of their needs, behaviours, and the environmental contexts in which they operate (Sondhi et al., 2024). This user-centred approach ensures that the eco-innovations developed are not only sustainable but also aligned with user expectations and market demands.

Also, the iterative nature of design thinking encourages experimentation and prototyping, which is vital for testing eco-innovative ideas before full-scale implementation (Pialot and Millet, 2020). By allowing for rapid prototyping and feedback loops, teams can refine their concepts to maximize both environmental benefits and user satisfaction. This iterative process also fosters collaboration among interdisciplinary teams, combining insights from design, engineering, and environmental science to create holistic solutions (Gajdzik and Wolniak, 2022a).

Design thinking promotes the exploration of alternative materials and processes that contribute to eco-innovations (Faludi and Agogino, 2018). By challenging conventional practices and considering sustainable materials, teams can reduce the ecological footprint of their products. The creative brainstorming sessions intrinsic to design thinking can lead to breakthroughs in developing eco-friendly technologies and practices, fostering a culture of innovation that prioritizes environmental responsibility.

The synergy between eco-innovations and design thinking is crucial for driving sustainable development (Munodawafa, 2024). By integrating environmental sustainability into the design process, organizations can create products that not only meet consumer needs but also contribute positively to the environment. This alignment not only enhances the competitive advantage of companies but also supports broader societal goals related to sustainability and environmental stewardship.

Combining design thinking and eco-innovation with open innovation offers a very exciting opportunity for organizations to develop a more sustainable approach within the context of creative collaboration. Accordingly, open innovation enables organizations to create, use, and share ideas, knowledge, and resources by reaching beyond their borders (Williamsson and Sandoff, 2023). It can therefore also provide a platform for various inputs and skills to support a co-creative process of

Table 1

The relations between life cycle assessment and eco-innovations.

Dimension	Life Cycle Assessment (LCA)	Eco-Innovations	Convergence of LCA and Eco-Innovations
Definition	LCA is a systematic process used to evaluate the environmental impacts of a product or service throughout its life cycle. This includes raw material extraction, production, use, and disposal.	Eco-innovations refer to the development of new or significantly improved products, processes, or services that contribute to environmental sustainability.	LCA can help identify and quantify the environmental benefits of eco-innovations through the determination of their impacts throughout their life cycle.
Objective	The main goal of LCA is to assess the environmental impacts of products or services to inform decisions that can reduce negative environmental outcomes.	The objective of eco-innovations is to introduce products, services, or processes that offer significant environmental improvements.	Both concepts are targeted at achieving environmental sustainability. LCA should, therefore, be capable of quantifying and guiding eco-innovations along the way.
Scope of Application	LCA can be applied to any product, process, or system, from raw material extraction to end-of-life disposal.	Eco-innovations apply to a wide range of areas, including energy, transportation, manufacturing, waste management, and agriculture.	LCA might act as a tool to check the scope of eco-innovations, so that over the completed life cycle, improvements achieved in some areas are not counterbalanced by deteriorations in others.
Methodology	LCA involves four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.	Eco-innovations involve creative thinking, technological development, and implementation of environmentally friendly solutions.	LCA methodology could feed into the eco innovation process data concerning environmental impacts, and provide underpinning to the design of innovations with lowered negative impacts.
Impact Focus	LCA focuses on identifying and quantifying environmental impacts such as energy use, carbon emissions, water consumption, and resource depletion.	Eco-innovations focus on reducing environmental impacts and improving sustainability, including reducing carbon footprints, waste, and resource consumption.	The meeting point is that LCA will help indicate where to focus to reduce the impacts and hence assist innovators towards improved sustainability.
Tools and Metrics	LCA uses metrics such as carbon footprint, water footprint, energy consumption, and other environmental indicators to measure impacts.	Eco-innovations may involve the development of new technologies, business models, or processes, often measured in terms of resource efficiency, emissions reduction, or waste minimization.	LCA provides quantifiable data that allows checking of the effectiveness of the eco-innovations. A common language and metrics are provided on the outcomes of eco-innovations.
Temporal Focus	LCA assesses long-term impacts by	Eco-innovations aim for both short-	The time orientation of LCA and eco-

(continued on next page)

Table 1 (continued)

Dimension	Life Cycle Assessment (LCA)	Eco-Innovations	Convergence of LCA and Eco-Innovations
Decision-Making Support	considering the entire life cycle of a product or service, from cradle to grave.	term and long-term improvements, with a focus on developing sustainable solutions that can be scaled and adapted over time.	innovation is complementary; LCA provides knowledge of long-term sustainability and eco-innovation is seeking short and long-term changes.
	LCA supports decision-making by providing detailed, quantitative data on the environmental impacts of different options or alternatives.	Eco-innovations drive decision-making by creating new opportunities for sustainable products, services, or processes.	It evidences the point of convergence between LCA and eco-innovations: decision-making is supported by both whereby LCA aids in the identification of the most sustainable innovations and further gives support to the implementation of such innovations.
Stakeholder Involvement	LCA is typically used by researchers, manufacturers, policymakers, and environmental analysts to assess and improve products' environmental performance.	Eco-innovations involve a broader range of stakeholders, including businesses, consumers, governments, and environmental NGOs, to create and promote sustainable solutions.	The convergence of LCA and eco-innovations will thus need collaboration from all stakeholders on the eco-soundness as well as practical feasibility of innovations.
Challenges	LCA can be resource-intensive and requires accurate data for all stages of the life cycle, which may not always be available.	Eco-innovations face challenges such as high initial costs, market resistance, and technological feasibility.	Convergence of LCA and eco-innovation could therefore address the above challenges through data evidence of long-term benefits of eco-innovations, justifying initial investment in them.

Source: Author's own work.

innovation (Yun et al., 2023). Building on this notion, the concepts of design thinking would provide means for organizations to adopt a more inclusive, user-centered approach in carrying out eco-innovations (Svirina et al., 2016; Yun et al., 2022, 2020).

Design thinking, in the context of open innovation, could be a platform for collaboration-customer, supplier, and competitor (Loderer and Kock, 2021). Such a collaborative setting presents tremendous opportunities for teams to really delve into an understanding of users and other stakeholders and their needs, behaviors, and environmental contexts where these actors operate. By being able to understand these factors, organizations can develop eco-innovations that would be sustainable but also in tune with market demand and user expectations (Gyamfi and Sein, 2021). In fact, the iterative nature of design thinking is complementary to the process whereby teams can experiment with, prototype, and refine ideas based on real-time feedback from a diverse group of contributors.

The emphasis on empathy and creativity inherent in design thinking would, therefore, provide a strong drive toward the exploration of alternative materials and processes within open innovation projects (Alaniz-Munoz et al., 2023). This presents an organization with an environment for questioning old practices and thus fostering brainstorming sessions that allow the involvement of a wide array of actors. It is such exploratory collaboration that leads to eco-friendly technologies

Table 2

Design thinking in sustainable product development.

Scope of research	Results	Source
Design thinking focused on sustainable product development, considering criteria of society, economy, and environment	Product testing Development of digital production in the context of Industry 4.0 Prototyping of handmade products	(Castiblanco Jimenez et al., 2021) (Ching et al., 2022; Soomro et al., 2021) (Li et al., 2019)
Creating conceptual frameworks of design thinking to support solving complex social problems within the framework of sustainable product development	Creating new value, reducing costs for society, addressing technical, organizational, and political issues	(da Costa Junior et al., 2019; Diepenmaat et al., 2020; Hoolohan and Browne, 2020; Maher et al., 2018; Matthews et al., 2019)
Integration of design thinking for creating innovations in the supply chain, including business model development, or improving company strategies towards sustainable development	Practices, culture, and political context of enterprises, reducing consumption	(Birkeland, 2022; Bonini and Sbragia, 2011; Dewberry and de Barros, 2009; Ferlito and Faraci, 2022; Geissdoerfer et al., 2016; Kozlowski et al., 2016; Nilsson and Göransson, 2021; Pyykkö et al., 2021; Santa-Maria et al., 2022)
Demonstrating the potential for seeking connections between human capital and environmental impact for the purpose of creating eco-innovative products	Eco-innovative products (green product design)	(Batwara et al., 2022; Yang et al., 2022),
Design thinking focused on open innovation	Enhanced collaboration and knowledge sharing leading to innovative sustainable solutions	Loderer and Kock, (2021); Alaniz-Munoz et al., (2023); Hawryszkiewicz and Alqahtani, 2020; Robins, 2018

Source: Own elaboration based on literature review.

and practices, thoroughly reducing the ecological footprints of goods and services.

It is explained by the synergistic interaction of eco-innovation and design thinking within the open innovation framework, which adds to increasing the quality of developed solutions and allows creating a culture of innovation oriented toward sustainability. Through this, organizations can provide products that meet consumer needs while helping take care of the environment. This would not only enhance their competitive advantages but also contribute to broader societal goals associated with sustainability and environmental stewardship.

3. Quality life cycle assessment method (QLCA)

The QLCA method (Quality Life Cycle Assessment) is a method for prospective qualitative-environmental assessment of product prototypes, based on which the most advantageous direction for product development is determined, while considering both product quality (customer satisfaction with usage) and environmental impact throughout its life cycle (LCA) (Gawlik et al., 2024; Siwiec and Pacana, 2024; Gajdzik et al., 2024). These prototypes are created with the voice of the customer (VoC) in mind by modifying the current states for key product criteria. The originality of the QLCA method lies in the integration of quality assessment with life cycle assessment, which has not been common so far, and its application during prototyping supports sustainable development. Development decisions are made based on an aggregated qualitative-environmental indicator (QLCA), which quantitatively determines the fulfilment of customer requirements while also assessing the environmental burden of the product throughout its life

cycle. According to QLCA, a ranking of product prototypes can be developed, according to which the decision-maker selects a prototype based on the established assumptions, including the production capabilities of the enterprise.

The QLCA method was developed during empirical research aimed at creating a coherent methodology and testing it on various products, as presented in (Gajdzik et al., 2024a; Gawlik et al., 2024; Siwiec and Pacana, 2024). According to these studies, the following procedure is proposed in the QLCA method:

- Stage 1. Preliminary analysis and selection of the reference product.
- Stage 2. Selection of the expert team.
- Stage 3. Definition of research objectives.
- Stage 4. Acquisition and processing of the voice of the customer (VoC).
- Stage 5. Definition of current and modified states of product criteria.
- Stage 6. Development of prototypes.
- Stage 7. Prospective assessment of the quality of product prototypes.
- Stage 8. Prospective assessment of the environmental impact of prototypes in LCA.
- Stage 9. Determination of the product development direction in terms of quality-environment.

A synthetic description of the individual stages of the QLCA method is presented in nine main stages.

Stage 1. Preliminary analysis and selection of the reference product. The QLCA method is applicable to any products, primarily those that are widely used among customers. This stems from the concept of the method, where the voice of the customer (VoC) is key in product development. Therefore, the product being analysed should be known and used by them, so that their requirements can be gathered in the most realistic way possible. This product may be in a mature phase or require improvement actions resulting from market research. Prototypes (alternative production solutions) are created based on the currently existing product (available for sale).

Stage 2. Selection of the expert team. For the effective implementation of the individual stages of the QLCA method, it is essential to assemble a team of experts who will support their execution. The team should be interdisciplinary and include, for example, designers and environmental experts, including those specializing in sustainable product development. The selection of the expert team can be conditioned by the assumptions presented in (Kupraszewicz and Żóitowski, 2002; Pacana and Siwiec, 2021). Typically, the expert team consists of four to fifteen experts (Fern, 1982; Krueger, 2014; Nyumba et al., 2018).

Stage 3. Definition of research objectives. When applying the QLCA method, the research objective should focus on determining the most satisfying product prototype (personalized for customers) that is also environmentally friendly throughout its life cycle (LCA). The research objective can be specified according to the SMART method, as presented in (Lawor and Hornyak, 2012).

Stage 4. Acquisition and processing of the voice of the customer (VoC). According to the assumptions of the QLCA method, product prototypes are created with consideration of customer requirements regarding the importance of product criteria and the quality of those criteria (in their current and modified states – anticipated as achievable and prototyped). It is assumed that customer requirements are gathered through surveys, questionnaires, or in-depth interviews (Hyman and Sierra, 2016; Pacana et al., 2023; Ponto, 2015). The minimum number of customers from whom requirements should be gathered can be determined according to the method presented in (Siwiec and Pacana, 2021). It is also possible to assume that it is necessary to gather expectations from at least 100 customers (Hyman and Sierra, 2016; Memon et al., 2020).

During exploratory research, customers indicate the product criteria that they consider essential, meaning those that are important to them and related to their level of satisfaction with the product. The number of criteria indicated by a single customer should include at least 10 unique criteria (Mu and Pereyra-Rojas, 2017). It is assumed that all indicated

criteria are assigned importance (weights) by customers, which can be given, for example, on a five-point Likert scale (Sullivan and Artino, 2013), or by distributing 100 points among them, where more points indicate greater importance of the criterion (Wolniak, 2018).

In establishing priorities for product changes, a ranking of product criteria is determined according to customer requirements. This is based on the fact that significant changes in customer satisfaction can be achieved by improving criteria that are important to customers. This involves transforming customer criteria into technical (measurable) criteria used by designers, referred to as qualitative criteria. Techniques such as correlation matrices, brainstorming (BM) (Putman and Paulus, 2009), or the popular QFD (Quality Function Development) method (Sakao, 2007) can be applied for this purpose. The generated technical criteria should be assigned corresponding weights (obtained from customers).

Stage 5. Definition of current and modified states of product criteria. It is assumed that the expert team assigns a current state to all technical (quality) criteria, which can be presented by its parameter in international metric units, e.g., value or range of values, such as length (m), or in the form of a description in the case of non-measurable criteria, such as the colour green. The current state represents the criterion in its present form and is included, for example, in the product catalogue (specification). A product expressed in its current state is a product available for sale (reference), representing a generalization of products of a given type (including applications).

Subsequently, hypothetical modifications to the current states of product criteria are proposed. For example, values or ranges of values above and below the current state value or range of the criterion. Brainstorming (BM) can be helpful in creating modifications to the criteria. Depending on the needs arising from the problem in seeking product modifications, more advanced techniques can be employed, such as the TRIZ method (Theory of Inventive Problem Solving) (Tandiono and Rau, 2022).

Stage 6. Development of prototypes. In this stage, various product solutions (alternative solutions, hypothetically created) are defined. They are created in the form of a model prototype described by sets of current and modified states of product criteria (proposed in the previous stage). Following the methodology presented, for example, in (Gajdzik et al., 2024a), each set of criteria states (current and modified) represents a different product prototype. It is necessary to develop at least 3, but no more than 10 prototypes (Mu and Pereyra-Rojas, 2017). These prototypes should be preliminarily analysed by the expert team in terms of, for example, production capabilities. If the developed prototypes deviate from the identified customer needs, including the actual resources of the company, they can be reduced to the most achievable options. Visualizing the prototypes, for example, through models or simulations in dedicated software, can be helpful.

Stage 7. Prospective assessment of the quality of product prototypes. This stage is conducted based on the previously proposed parameters of the criteria states (current and modified). It is also possible to evaluate the offered product prototypes by experts and customers, for example, on a scale from 0 to 1 (Gajdzik et al., 2024b; Siwiec and Pacana, 2024), or using a fuzzy Saaty scale (Gawlik et al., 2024). The values of the parameters or expert assessments can be processed using appropriately selected techniques. According to the developed approaches consistent with the QLCA methodology, it is effective to apply, for example:

- The Entropy method, as in (Siwiec and Pacana, 2024) – a commonly used method that considers the weights of criteria, which supports the analysis of value dispersion in the decision-making process, where a greater degree of dispersion indicates a higher degree of data diversity, applicable in analysing various parameters for the offered prototypes; among other multi-criteria decision-making (MCDM) methods, this method is distinguished by limiting human intervention in the analysis of prototypes, thus increasing the objectivity of

results in the form of their comprehensive assessment (Zhu et al., 2020);

- The Weighted Sum Model (WSM), as in (Gajdzik et al., 2024b) – one of the least complicated MCDM methods, which allows for calculating the quality of prototypes based on expert assessments regarding the quality of prototype criteria and the weights of those criteria;
- Or the FAHP method (Fuzzy Analytic Hierarchy Process), as in (Gawlik et al., 2024) – a popular decision-support method based on assessments in a fuzzy Saaty scale, applicable to solving decision-making problems in a suitably selected expert team, where its main advantage is the reduction of subjectivity by using triangular fuzzy numbers to assess the quality and weights of prototype criteria (Kwong and Bai, 2002).

The results from the prospective assessment of the quality of product prototypes (regardless of the method used) are presented according to the O index, which is relevant to the final index of the selected method for its calculation. The O index presents the quality values of the prototypes, which are normalized for further analysis (Gajdzik et al., 2024a; Gawlik et al., 2024; Siwiec and Pacana, 2024), as shown in formula (1):

$$Q_j = \frac{O_j - \min O_j}{\max O_j - \min O_j} \quad (1)$$

where: O – quality value of the prototypes obtained from any selected method, Q – normalized quality value of the prototypes, j – product or prototype, j = 1, 2, ..., n.

The quality index values of the prototypes (Q) should range from 0 to 1, where 0 represents the least favourable prototype in terms of quality, and 1 represents the most favourable prototype in terms of quality. Therefore, according to the Q index, all analysed prototypes can be ranked in a single ranking. Based on this ranking, it is possible to select the prototype that will meet customer expectations to the greatest extent.

Stage 8. Prospective assessment of the environmental impact of prototypes in LCA. Next, a prospective life cycle assessment (LCA) of the product prototypes is conducted. For this to take place, it is essential to perform a traditional LCA method based on the current states of the criteria of the reference product. The LCA method for the reference product is carried out in accordance with the ISO 14040 standard (Finkbeiner et al., 2006), which includes the stages of defining goals and scope (e.g., functional unit, system boundaries, data), inventory analysis (data collection, calculating inputs and outputs, data standardization), impact assessment (modeling data according to the adopted assumptions), and interpretation (validation for the selected environmental impact criterion and conclusions) (Proske and Finkbeiner, 2020). The estimated environmental burden value for the specified criterion, calculated for the reference product, serves as the value for modeling the environmental burden of the prototypes of that product. As adopted in the QLCA methodology presented in earlier studies, e.g., (Gajdzik et al., 2024b; Gawlik et al., 2024; Siwiec and Pacana, 2024), the environmental burden of prototypes in LCA is calculated: i) based on the values of environmental criteria in the life cycle of these prototypes estimated by experts, as proposed in (Siwiec and Pacana, 2024), or ii) in a simplified manner by modeling the change in environmental burden in relation to the percentage value of qualitative changes in the criteria, e.g., using the Pareto principle, as adopted in (Gajdzik et al., 2024b) (2):

$$EI_j = EI_i \pm (0.20 \times EI_i) \quad (2)$$

where: EI – environmental burden value in the life cycle, j – prototype, i – reference product, i, j = 1, 2, ..., n.

Thus, the estimated environmental burden values for the reference product and its prototypes (EI) are normalized similarly to the quality index values (Q). This results in the environmental impact index value in the life cycle (LCA), as shown in formula (3) (Siwiec and Pacana, 2024):

$$LCA_j = \frac{\max EI_j - EI_j}{\max EI_j - \min EI_j} \quad (3)$$

where: EI – the value of the environmental burden estimated for the reference product or prototypes, j – product or prototype, j = 1, 2, ..., n.

Following the developed QLCA methodology, the values of the environmental impact indicator in the life cycle of prototypes (LCA) should range from 0 to 1, where 0 represents the least environmentally friendly prototype and 1 represents the most environmentally friendly prototype. Therefore, according to the LCA indicator, all analysed prototypes can be ranked in a single ranking. Based on this ranking, it is possible to select the prototype that will be the most environmentally friendly throughout its life cycle.

Stage 9. Determining the direction of product development in terms of quality-environment. In the final stage of the QLCA method, the quality indicator (Q) and the environmental indicator (LCA) are aggregated into a single quality-environmental indicator (QLCA). The aggregation is created according to the most popular approach presented in (Langhans et al., 2014). This is an additive aggregation, meaning the arithmetic mean of the quality and environmental indicators is calculated, as shown in formula (4) (Gajdzik et al., 2024b; Gawlik et al., 2024; Siwiec and Pacana, 2024):

$$QLCA_j = \frac{Q_j + LCA_j}{2} \quad (4)$$

where: Q – quality indicator, LCA – environmental impact indicator in the life cycle, j – prototype, j = 1, 2, ..., n.

The higher the value of the QLCA indicator, the more advantageous the prototype is in terms of both quality and environmental impact throughout its life cycle. This means that it has a quality that is as satisfying as possible for customers and is also as environmentally friendly as possible.

Based on previous studies, e.g., (Gawlik et al., 2024), the verbal interpretation of the QLCA indicator can be made using a scale of relative states (Kolman, 1992), as shown in Fig 2.

On the other hand, for the preliminary selection of prototypes according to the QLCA indicator, the IPA model (importance-performance analysis) (Kim and Oh, 2001; Sever, 2015) can be applied, which supports the determination of the direction of product development in terms of quality-environment. The concept of Modified Importance-Performance Analysis (IPA) model was presented in the (Gajdzik et al., 2024b).

Modified Importance-Performance Analysis (IPA) model that helps in identifying and selecting the most favourable product prototypes in terms of both quality and environmental impact. The model provides a visual representation of the relationship between the importance of product features (or design criteria) to customers and the performance of these features in the developed prototypes. This approach is specifically adapted for the proposed QLCA framework (Quality Life Cycle Assessment), allowing the assessment of prototypes not only from the quality perspective but also with respect to their environmental footprint.

The modified IPA model integrates two key factors: the quality satisfaction of customers and the environmental performance of the product in its life cycle. By plotting these aspects on a two-dimensional matrix, it becomes easier to visualize how different prototypes perform across these criteria. The model helps in guiding design and development teams to prioritize prototypes that perform well both in terms of customer satisfaction and environmental sustainability. The goal is to ensure that the final product aligns with both market demands and sustainability goals.

Based on the modified IPA, solutions that are the most environmentally friendly and meet customer quality expectations to the highest degree are selected. This is the final stage of the QLCA method. A detailed description of the QLCA method is presented in, for example,

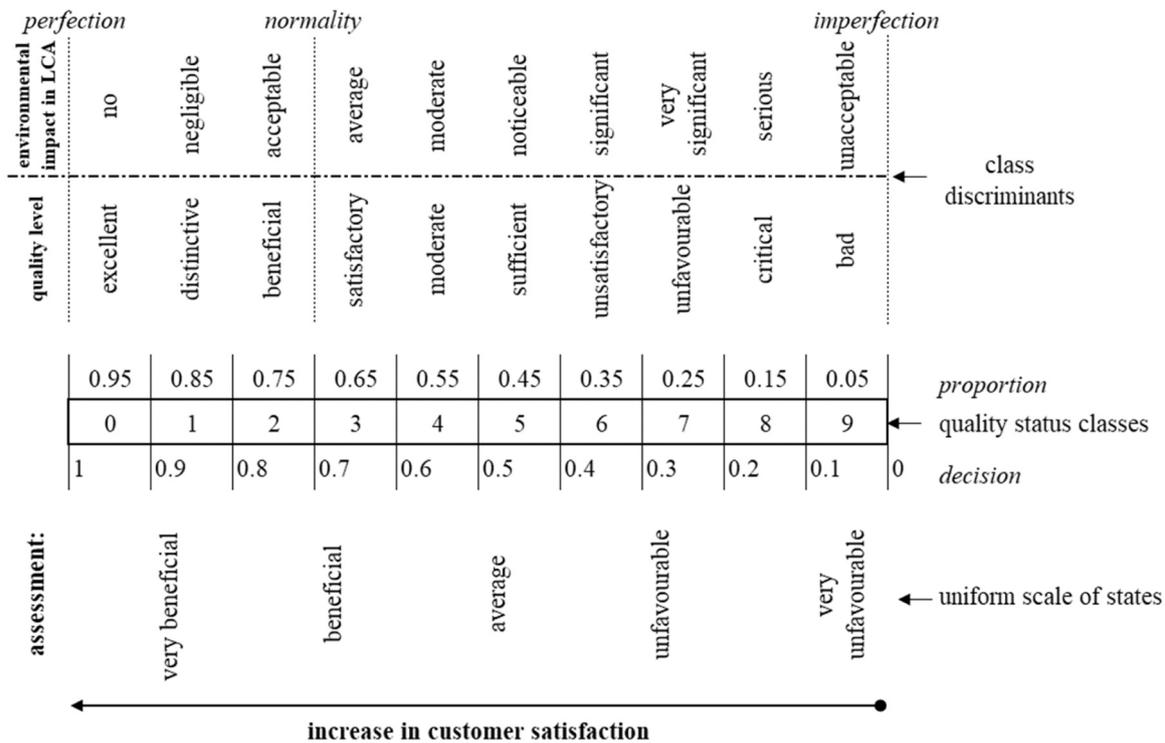


Fig. 2. Scale of relative states for the analysis of the QLCA indicator. Source: Own elaboration based on (Gawlik et al., 2024).

(Gajdzik et al., 2024a; Gawlik et al., 2024; Siwiec and Pacana, 2024)

4. Model framework of design thinking and QLCA method (DT-QLCA)

4.1. General research approach

The idea of the research focused on the implementation of an innovative method called Quality Life Cycle Assessment (QLCA) in the design thinking process (DT-QLCA), as presented in (Gajdzik et al., 2024a; Gawlik et al., 2024; Siwiec and Pacana, 2024). This research was aimed at developing a model framework DT-QLCA. The research concept included increasing the efficiency of the design process and improving products towards their sustainable development at the early stages of product development. This is achieved through multidimensional creation, evaluation, and interpretation of production capabilities based on current design solutions. Therefore, a key stage where the DT-QLCA method is applied is the prototyping phase. At this stage, various product solutions are sought within the processing of multi-criteria decision-making problems based on the analysis of selected aspects of sustainable development – in this approach, these are quality (customer satisfaction with the product’s use) and environmental impact (environmental burden in the product’s life cycle).

4.2. Description of implementation of DT in QLCA (DT-QLCA)

In order to standardize the developed framework, five main stages of design thinking were established (empathize, define the problem, ideate, prototype, test). However, the stages included in the proposed framework are identical to the stages of the QLCA method (as in Section 3). The adopted concept of implementing DT into QLCA (DT-QLCA) is extended with the proposed approach to evaluating ideas using MCDM considering the following criteria (Gawlik, 2008), i.e.:

- need for environmental impact assessment.
- sustainability as a design priority.
- need for comparison of alternative solutions.
- reduction of design error risk.
- requirement of multi-criteria prototype analysis.
- emphasis on ecological innovation (eco-design).
- effectiveness of life cycle monitoring.
- better environmental risk management.

Proposed DT-QLCA is presented in Fig 3.

A detailed description of the incorporation of individual stages of the QLCA method into the design thinking process is presented, divided by the phases of this approach.

4.2.1. Phase 1. Empathize

The traditional approach to design thinking begins with empathy, which involves cognitive activities. It has been observed that during the empathize phase, it is appropriate to implement the first and second stages of the QLCA method, namely: preliminary analysis and selection of the reference product, as well as the selection of a team of experts.

This is due to the fact that a significant aspect of empathy is understanding the tasks that the manufacturing enterprise will have to undertake. This is based on the existing needs of customers, the current practices of the company, but also the hidden (internal) motivations of decision-makers that determine the adopted course of action in product development. Conducting observations and analyses of the environment in relation to future actions in this phase, and tools such as empathy maps or ethnographic interviews can be useful. If possible, it is appropriate to use more advanced techniques, such as the Kansei method (Yamagishi et al., 2018).

Consequently, similar to the QLCA method (stage 1), it is assumed that the design thinking framework based on QLCA (DT-QLCA) is applicable to any products, provided that they are existing products on the market (available for sale) and are widely known and/or used by customers. The choice of product depends on the needs of the entity applying the method and may depend, for example, on the needs for the

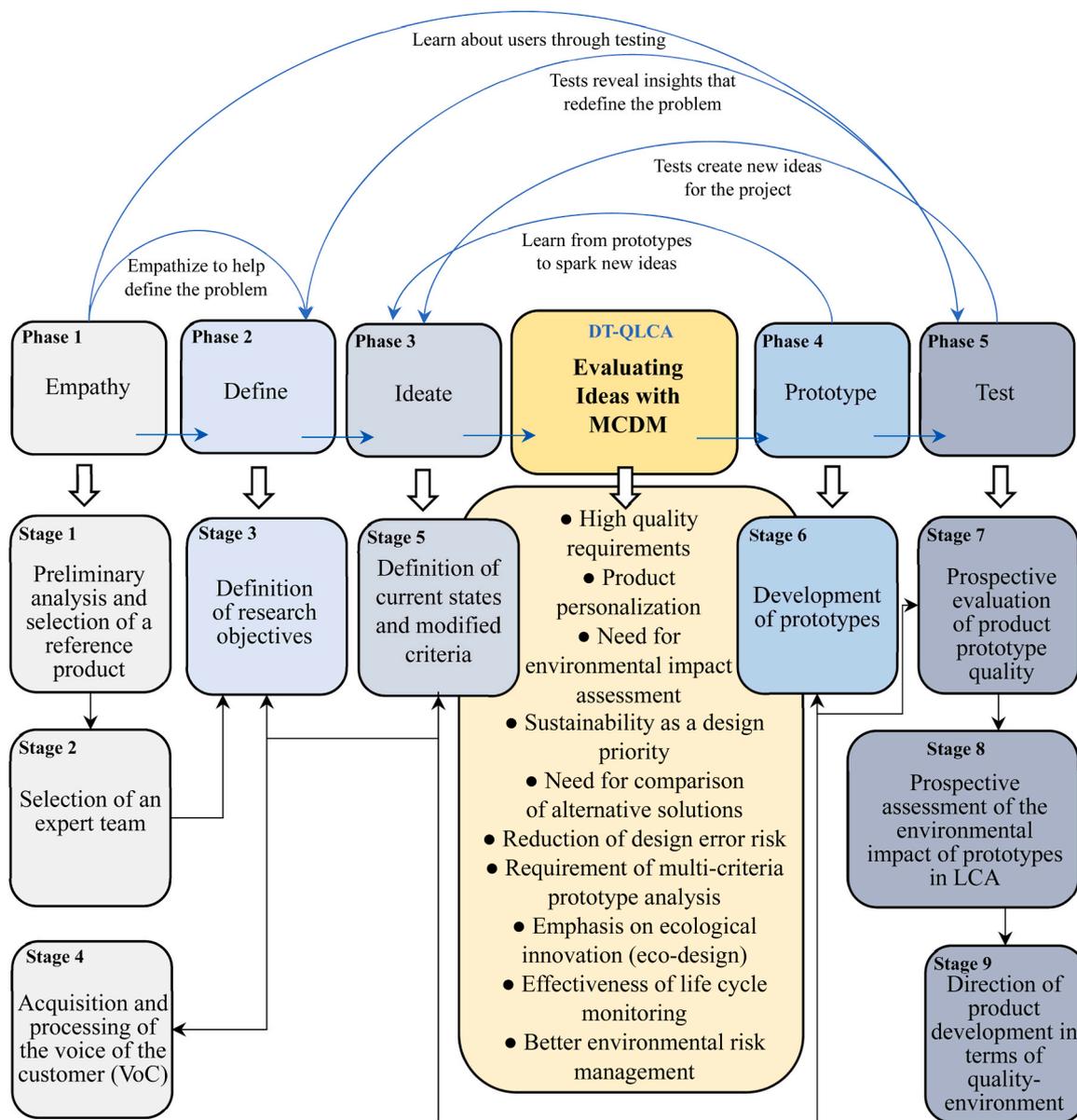


Fig. 3. The concept of design thinking incorporating the QLCA method (DT-QLCA)
Own elaboration

development of current products that are in the maturity phase, or on market dynamics.

Also, design thinking is a nonlinear, iterative process that should be carried out by a suitably selected expert team. Therefore, it is assumed that the team will support the implementation of all stages of the proposed approach. The selection of the team occurs as in the QLCA method (stage 2). Furthermore, as noted by (Brodnicki, 2015), the design thinking approach recommends avoiding techniques that focus solely on the expert team, such as focus groups. This is based on the belief that customers tend to adjust their beliefs to those of others, thereby avoiding expressing individual opinions. Supporting the cognitive process among potential customers can contribute to initiating inspiration in the development of future products. As a result, it is expected to obtain a set of data, the quantity of which will depend on the scope of the research conducted, including the complexity of the analysed issue. The research material should serve as an input element for a real description of the problem, which is related to creating innovative approaches that break existing thought frameworks.

4.2.2. Phase 2. Defining the problem

Based on design thinking, the next phase concerns defining the research problem. Therefore, it was deemed appropriate to include the third stage of the QLCA method in this phase, namely: defining the research objective.

In the proposed approach, the research problem relates to the issues of designing and improving products in accordance with the idea of sustainable development, including the search for eco-innovative product solutions in terms of quality and environmental aspects. Thus, the research problem is focused on answering the following question: 'How to design a product that has the highest quality while simultaneously minimizing its negative impact on the environment in its LCA?' The formulated research question is merely a reflection of the proposed research methodology and can be modified depending on the needs of the enterprise. Techniques for quality management, such as the 5Why method or 5W2H (Tari and Sabater, 2004), can be helpful in defining the problem. Subsequently, in relation to the defined research problem, the research objective is established. The course of action is appropriate as presented in the QLCA method (stage 3).

4.2.3. Phase 3. Generating ideas

Generating ideas constitutes the third phase of design thinking, which involves developing hypotheses regarding the previously defined problem and preliminary prototyping. In this phase, it was decided to include the fourth and fifth stages of the QLCA method, namely: obtaining and processing the voice of the customer (VoC) (Shen et al., 2022) and subsequently defining the current and modified states of product criteria.

Incorporating VoC at the early stages of product development promotes the proper direction of design and improvement activities to meet customer expectations. VoC is obtained through popular techniques, such as surveys, questionnaires, or in-depth interviews if there is a need to supplement survey results (Hyman and Sierra, 2016; Ponto, 2015). Exploratory research, including the method of processing their results to select key customer criteria, as well as the process of creating modifications to the current states of criteria, is conducted according to the fifth stage of the QLCA method.

4.2.4. Phase 4. Prototyping

Prototyping involves outlining various product solutions (alternative solutions). Analysing the design thinking approach, it was deemed appropriate to expand this phase with the methodological approach proposed in the sixth stage of the QLCA method, which concerns the development of product prototypes. The course of action is appropriate as in the sixth stage of the QLCA method.

Additionally, considering the assumptions in the traditional approach to design thinking, it is assumed that the developed prototypes should be preliminarily analysed by the expert team in terms of, for example, production capabilities. If the developed prototypes deviate from the identified customer needs, including the actual resources of the company, they can be reduced to the most achievable options. Visualizing prototypes, for example, through models or simulations in dedicated software, can be helpful.

4.2.5. Phase 5. Testing

Based on the developed prototypes, the testing phase is conducted. The testing phase is carried out according to the previously selected criteria, and depending on the type of prototypes, an appropriate testing method should be chosen (Bender-Salazar, 2023). It is also important at this stage to gather feedback from customers to create a collection of different perspectives (Brodnicki, 2015). The testing phase should take place in the most realistic environment possible, as the test results will indicate whether the proposed solutions are accepted or rejected.

It is suggested to modify the traditional approach to the testing phase by expanding it with the following stages from the QLCA method, namely: prospective assessment of the quality of product prototypes (stage 7), prospective assessment of the environmental impact of prototypes in LCA (stage 8), and determining the direction of product development in terms of quality-environment (stage 9). Therefore, according to the proposed QLCA methodology, it is recommended to conduct tests considering the quality criterion (customer satisfaction with the product's use) and the environmental burden criterion in the product's life cycle (LCA). The results obtained after analysing these criteria are aggregated within the simultaneous interpretation of the results in terms of quality and environmental aspects, after which the direction of design or improvement actions is determined in the context of sustainable product development. The course of action is appropriate as in the QLCA method presented for stages seven, eight, and nine.

As a result, a five-phase framework for design thinking has been developed, incorporating nine stages consistent with the QLCA method. The DT-QLCA model framework is presented in Table 3.

The developed framework of design thinking is useful at the stage of eco-innovation for product designers in their sustainable life cycle. The framework model can have a significant impact on the process of promoting and deepening design thinking among managers and designers towards reducing negative environmental impacts while simultaneously

Table 3
DT-QLCA model framework.

Design Thinking Phase	QLCA Model Stages	Supporting Techniques	Expected Outcome
Empathize	Preliminary analysis and selection of a reference product	Market research, empathy map, ethnographic interviews, Kansei method	Data supporting the correct definition of the problem and gathering initial customer requirements; selected product for analysis
Define the Problem	Selection of an expert team Definition of research goals	Expert team selection methods SMART(-ER) method	Interdisciplinary team of experts Defined research problem and research objective
Ideate	Acquisition and processing of the voice of the customer (VoC)	Survey, questionnaire, interview, correlation matrix, brainstorming, QFD	Customer requirements for essential product criteria, including the importance of criteria and satisfaction with their quality
	Definition of current states and modified product criteria	Brainstorming, catalogue (specification)	Defined current states of criteria and initially determined modifications
Prototype	Development of prototypes	Brainstorming, computer simulations	Product prototypes
Test	Prospective evaluation of prototype product quality Prospective evaluation of the environmental impact of prototypes in LCA	Quality assessment techniques, e.g., Entropy, WSM, FAHP ISO 14040 standard, modeling using an expert team, Pareto principle	Results from the quality assessment of product prototypes Results of the environmental impact assessment of the product

Source: own elaboration.

striving to meet future customer requirements

5. Discussion

5.1. The incorporation of design thinking into LCA concept

It has been demonstrated that it is possible to incorporate the concept of design thinking incorporating the QLCA method (DT-QLCA), which is based on simultaneous, prospective assessment of product prototypes according to their quality and environmental impact throughout their life cycle. The main anticipated benefits of the design thinking framework based on the QLCA method, i.e. DT-QLCA, include:

- Designing and improving products while considering customer expectations and simultaneously addressing their environmental impact throughout the life cycle;
- Supporting the product prototyping process by modifying the current states of product criteria and subsequently creating alternative product solutions based on them;
- Ensuring prospective assessment of the quality and environmental burden of product prototypes in the life cycle (LCA), including the aggregation of results within the simultaneous interpretation of prototypes in terms of their sustainable development;
- Reducing resource waste through methodical support for decision-making, including ensuring the anticipation of key investment actions on the path to sustainable product development.

The results of this paper demonstrate the viability of integrating the

concept of design thinking incorporating the QLCA method to foster eco-innovation in sustainable product development. By aligning customer-centric innovation with environmental sustainability, the proposed framework addresses a critical gap in traditional product design methodologies, which often neglect comprehensive environmental considerations. The findings underscore that embedding QLCA into design thinking processes allows companies to systematically assess both the quality and environmental impact of product prototypes, leading to more balanced and sustainable design outcomes.

Important outcome of this integration is the enhancement of decision-making processes in product development. The DT-QLCA model allows designers to evaluate multiple product prototypes based on dual criteria: customer satisfaction and environmental burden. This holistic approach to product evaluation ensures that sustainability considerations are not compromised in favour of market demands. The framework's prospective assessment methodology allows for the identification of design choices that minimize resource use, emissions, and waste at every stage of the product's life cycle, from material sourcing to disposal. This proactive consideration of environmental impact throughout the design process is a significant advancement over traditional methodologies, which often address sustainability as an afterthought, typically during the later stages of product development or post-production.

The study's results also emphasize the practicality of the DT-QLCA-based design thinking framework in real-world applications, particularly for managers, designers, and decision-makers in manufacturing and R&D environments. By providing a clear and structured process for evaluating environmental and customer-related outcomes, the framework facilitates more informed decision-making, helping organizations align their product designs with sustainability goals without sacrificing market competitiveness. The potential for this framework to reduce waste, optimize resource use, and improve overall product quality positions it as a valuable tool for companies aiming to transition toward more sustainable business practices.

5.2. The relation of proposed method with FMEA failure mode and effect analysis)

Even though our results are not directly corroborated by it, the Social Failure Mode and Effect Analysis (FMEA) framework proposed by Spreafico and Sutrisno (2023), show some common reasoning lines, leaving a possibility for integration of both approaches (in a separate research, though). The FMEA offers several qualitative advantages that enhance sustainable product development, which could prove useful in DT-QLCA applications. These are:

1. Enhanced decision-making:
 - a. comprehensive risk assessment – the combination of DT-QLCA and AI-assisted FMEA allows for a more thorough evaluation of potential failure modes in product design; AI-enhanced FMEA could analyze vast risk-related datasets, while our DT-QLCA would ensure risk-assessment in the sustainability context throughout the entire product lifecycle.
 - b. improved customer alignment – DT-QLCA helps understanding customer needs through DT principles, while FMEA focuses on identifying and mitigating risks that could affect customer satisfaction; merging these two approaches could offer a higher level of customer alignment.
2. Increased innovation:
 - a. facilitated eco-innovation – the integration of both frameworks boosts the environmental aspect of eco-innovation by combining DT-based problem-solving (DT-QLCA) with systematic risk analysis (FMEA);
 - b. interdisciplinary collaboration – both frameworks promote collaboration among diverse teams, including designers, engineers, and sustainability experts.

3. Systematic evaluation:

- a. structured framework for sustainability – the integration of FMEA's structured approach with the iterative nature of DT-QLCA offers an opportunity of establishing a systematic methodology for evaluating sustainability at each stage of product development;
- b. continuous improvement – both frameworks strongly support continuous improvement in product design; FMEA results could inform future iterations of the design process within the DT-QLCA framework; this in turn would allow the companies to design their products based on real-world performance and sustainability metrics.

5.3. The limitations of proposed framework

The results reveal certain limitations of the proposed framework. The focus on a single environmental burden criterion in the QLCA method may limit the comprehensiveness of environmental assessments, potentially overlooking other critical sustainability factors. Additionally, the reliance on modeling and inventory data in environmental assessments may not fully capture the complexities of real-world production environments. These limitations suggest that further research is needed to refine the QLCA framework, particularly in expanding the range of environmental criteria evaluated and improving the precision of life cycle impact modeling.

5.4. The relations of proposed framework with innovation theory

The results of the paper align closely with innovation theory, particularly in how eco-innovation and sustainable product development are framed within the context of design thinking. Innovation theory, especially models like the diffusion of innovation and disruptive innovation, emphasizes the role of novel solutions in addressing emerging market needs and societal challenges (Wurster et al., 2024). The integration of QLCA into design thinking presents a clear embodiment of eco-innovation, where environmental sustainability becomes a central component of the innovation process. The model framework (DT-QLCA) described in the paper allows companies to develop products that not only satisfy customer expectations but also minimize their environmental footprint, reflecting an important evolution in how innovation is understood in contemporary business practices.

Important aspect of innovation theory is the idea that innovations must offer new value, either through technological advancements, new processes, or novel uses of resources (Spinnewijn et al., 2024; Faridizad et al., 2024). The results of the paper demonstrate how QLCA, when integrated into design thinking, facilitates innovation by systematically assessing the environmental impacts of different product prototypes at an early stage of development. This approach ensures that companies can innovate by reducing resource consumption, waste, and environmental impact without sacrificing product quality or customer satisfaction. This dual focus enhances the potential for innovation by aligning technological progress with sustainability goals, which is increasingly recognized as a key driver of competitive advantage in innovation theory.

The results also align with the concept of responsible innovation, which suggests that new products and services should address not only market demands but also broader societal and environmental issues (Tantiyaswasdikul, 2024). By integrating QLCA, the framework ensures that sustainability is embedded into the innovation process, enabling companies to respond to growing consumer demand for eco-friendly products. This integration supports the notion in innovation theory that responsible innovation is essential for long-term success, as businesses are increasingly held accountable for their environmental impact. The paper's findings show that this integration leads to more sustainable product designs, thus reinforcing the idea that responsible innovation can drive market differentiation.

The iterative nature of design thinking, which encourages continuous prototyping and feedback, is also enhanced by the QLCA framework (Kayyali, 2024). Innovation theory often highlights the importance of feedback loops and iterative processes in the development of successful innovations (Aris et al., 2025). By incorporating environmental assessments throughout the prototyping phase, companies are able to refine their designs in ways that traditional product development methodologies may overlook. This iterative, data-driven approach to eco-innovation aligns with theories that emphasize the importance of adaptation and learning in the innovation process (Hernandez-Ramirez et al., 2024).

The DT-QLCA model framework challenges traditional views of innovation as primarily driven by technological advancements, by showing that innovation can also be process-oriented. The framework facilitates innovation by improving the decision-making processes within companies, ensuring that environmental impact is considered as a critical factor alongside customer satisfaction. This aligns with theories of process innovation, where improvements in the way products are developed, rather than in the products themselves, lead to competitive advantages (Leão et al., 2024). In this implementation (application), changes based on ICTs help companies, it is especially important in industrial sectors that heavily influence the environment, e.g. (Gajdzik and Wolniak, 2021; Gajdzik et al., 2025).

The proposed framework is a complex, interconnected process where every phase of a product's life cycle impacts the overall system. Systems thinking emphasizes the interdependence of various elements, suggesting that sustainability and customer satisfaction cannot be viewed in isolation (De Angelis and Ianulardo, 2024; Dilip and Kerr, 2024; Valentinov, 2012). The paper's results align with this theoretical approach by demonstrating that evaluating both environmental and quality metrics concurrently leads to more comprehensive decision-making. The DT-QLCA allows companies to foresee the environmental consequences of design choices across a product's entire life cycle, fostering an approach that integrates material sourcing, production, use, and disposal in a holistic manner. This interconnected perspective is central to systems thinking, where any change in one part of the system affects the entire outcome. The DT-QLCA methodology, with its life cycle focus, embodies this systems-based view by addressing both environmental and market forces simultaneously.

5.5. The potential of proposed framework in open innovation

Results in this paper point to a very valuable intersection of design thinking and QLCA with the concept of open innovation. The proposed model for DT-QLCA will incorporate QLCA into design thinking to provide an approach drawing on customer-centered innovation and environmental assessment. This double emphasis gives an open environment for innovation, where insights from many disciplines—such as environmental sciences, engineering, and customer feedback—come into product development. The DT-QLCA model is fitted within the open innovation framework since it allows the openness of stakeholders in multiple stages of design that facilitate both external and internal ideas to converge into one framework. The model, therefore, supports the larger objectives of open innovation, which focus on the pooling of knowledge, creativity, and technological insights from diverse sources for more robust and sustainable innovations.

Open innovation, with its emphasis on external collaboration and interdisciplinary inputs (Yun et al., 2020; Li et al., 2024), is closely related to the core objectives of the DT-QLCA framework. The model provides an environment whereby companies are able to get feedback not only from customers, but also from experts in environmental matters and other players in the same industry; hence, this allows for the sharing of information that may be indispensable in the sustainable development of a product. In this open innovation platform, it is expected that firms are able to think outside the box of traditional, closed cycles in the development of products that usually ignore considerations about

environmental impact or delay them. Instead, it is the DT-QLCA model that allows sustainability assessments to be imbedded within the whole design thinking process for more informed and responsible decision-making. The iterative nature of the DT-QLCA framework also consorts well with principles of open innovation because continuous prototyping, testing, and refinement can be allowed by both customer and environmental feedback (An and Mikhaylov, 2024; Kratzer et al., 2017; Meidute-Kavaliauskiene et al., 2021; Yun et al., 2024). The feedback mechanism is an adaptive innovation process open to modification and improvement from both quality and life cycle environmental impact metrics. Multidisciplinary in nature, the framework assures that eco-innovation is an outcome rather than an end goal from a structured and collaborative methodology (Asad et al., 2023; Bigliardi and Filippelli, 2022; Wnuk and Runeson, 2013). Collaboration brings benefits to the companies, in fact, thanks to a wide view of early anticipation and integration of market and environmental demands in the phase of design, it is possible to come up with products closer to sustainability objectives (Turoń, 2022; Lippolis et al., 2023).

The proposed DT-QLCA model underlines the role of transparency into innovation as one of the key factors for open innovation. While corporations apply this tool, they reveal their concerns in the production of eco-friendly product design, further developing strategic positioning within a more robust marketplace or drawing in customers who are sensitive to environmental causes. Its inclusion of QLCA makes the model an unambiguous, quantifiable analysis methodology for environmental impact, therefore enhancing the transparency and accountability of a corporate entity's sustainability undertaking. This transparency is not only in line with open innovation but also instills a sense of trust in consumers and stakeholders who increasingly value corporate responsibility in environmental stewardship.

The integration of open innovation within a DT-QLCA framework represents a paradigm shift in companies' product development processes while considering customer demand and sustainability. This will drive forward an inclusive, flexible pathway to eco-innovation where companies can meet and consider different viewpoints on a broad knowledge base. Hence, more resilient and sustainable product designs will be developed that meet environmental and market demands.

5.6. The implementation of design thinking in following phases of LCA

Table 4 gives an overview of a structured application of Design Thinking with Quality Life Cycle Assessment in three critical phases of open innovation: initiation, development, and realization. This start is made during the initiation phase when a proper foundation is laid down with the DT-QLCA approach through ideation and problem definition in such a way that the relevant external stakeholders get identified for integration into the development process regarding, for instance, consumers, suppliers, and environmental experts. This collaboration will inform not only the product goals but align them with sustainability objectives and customers' needs, all based on quantifiable environmental impact metrics along the life cycle of the product. In this respect, the DT-QLCA framework allows for rapid prototyping and iterative refinement in the development phase through the combination of customer-centered design with rigorous environmental assessments. Here, prototypes are evaluated against criteria along various qualities of a life cycle assessment, such as resource consumption and emission, which enables teams to go back and refine their designs, informed by internal knowledge and external feedback. This iterative process illustrates open innovation principles through the call for collaboration between cross-functional teams and stakeholders in the co-creation of environmentally responsible prototypes (Yun et al., 2022; Yang et al., 2024; Wang et al., 2023). Finally, during the realization stage, the DT-QLCA framework helps make informed final decisions with regards to product designs. Companies shall aim to better their production practices concerning better resource efficiency and ecological footprints through QLCA-informed analysis, conforming to the set sustainability

Table 4
The design thinking in quality life cycle assessment in phases.

Open Innovation Phase	The Usage of Proposed Approach
Initiation	The DTQLCA approach, in the initiation stage, allows the ideation and problem-definition activities from an early beginning to integrate QLCA. Third-party stakeholder input in the form of consumer views, inputs from suppliers, and environmental experts is elicited actively to determine product goals consistent with sustainability and customer needs. Empathy and collaborative brainstorming are key in this phase of Design Thinking, bringing together diverse views to create a vision for the product that is centered on the environment and the user. The QLCA methodology will make sure that such ambitions trace their roots back to metric-based environmental impact assessment over the life cycle of the product.
Development	The DT-QLCA framework embeds customer-centered design with comprehensive environmental assessment, thus supporting prototyping and iterative improvement in development. Several prototypes are reviewed for QLCA criteria such as resource consumption, emissions, and customer satisfaction metrics that enable teams iteratively to refine designs in response to both internal expertise and external feedback. In the iterative collaborative refinement process, the product choices get validated through sustainability metrics and market relevance. This applies open innovation principles through cross-functional teams co-creating with stakeholders on creating environmentally sound prototypes.
Realization	In the realization stage, the DT-QLCA framework will support final decision-making on the most feasible product design with clear criteria regarding the quality and environmental impact assessments. The company will apply production practices through QLCA-informed analysis that will result in maximum efficiency in resource use while causing minimum ecological impact; the product will conform to sustainability objectives. Previously established loops of feedback revisit stakeholders again for further validation, allowing the ongoing adjustments in product design and materials to keep up with market demand and standards of sustainability. The DT-QLCA methodology thus increases the transparency and accountability that enables products to be environmentally adequate and valued by consumers while going to market.

objectives. The previously developed feedback mechanisms are revisited for validation of the product against market demands and standards of sustainability, which promotes still a culture of transparency and accountability in the process. The expectations of consumers are met with this holistic approach as the product goes to market, furthering environmental stewardship.

Several guidelines need to be observed when applying the model in managerial practice. (I) Methodological guidelines reflect the Design Thinking methodology and requires from the decision-maker to: (i) embrace iteration (DT is not a linear process, it requires revisiting former stages, and anticipating those further in the model-design ladder); (ii) foster a user-centric culture (engage with users at many occasions throughout the decision-making process); (iii) effectively prioritize ideas (with use of structured, brand- or process-specific frameworks); (iv) promote open mindsets (allow mistakes and thinking out-of-the-box); (v) employ rapid prototyping (create and test prototypes early in the process); (vi) utilize brainstorming (diverse methods and techniques); (vii) map the whole process (write down the milestones, create documents, keep a journal); (viii) embrace team interdisciplinarity and diversity (collaborate across scientific disciplines, branches of industry, public offices). (II) Model-specific guidelines are the following: (i) the studied product should be widely used and well-known to potential customers – this will enhance the model's effectiveness and ensure realistic results, mainly due to the need for incorporating the Voice of the Customer (VoC) at the initial stages of the model, with subsequent stages depending on the VoC; (ii) it would be beneficial to have an expert conducting product's LCA – acquiring dedicated LCA computer software

would be useful (i.e. OpenLCA, SimaPro, Gabi or others); (iii) it is most important to properly identify the primary environmental impact criterion to be analyzed in product's LCA – our model allows for the consideration of one criterion per analysis; (iv) as in the methodological, DT-related guidelines, forming an interdisciplinary team of experts facilitates complex, multi-criteria decision-making.

The DT-QLCA model requires an implementation structured but flexible for its proper execution, matching its nature-iterative, collaborative, and interdisciplinary. Professionals will have to interface with different components of the model: Empathy, Definition, Ideation, Prototyping, and Testing, but always keep in focus the integration of customer-centered insights with environmental aspects along the whole life cycle of the product. Presented herein are comprehensive directives intended to assist practitioners in the application of this model: Initially, it is imperative for practitioners to engage in meticulous preparation during the Empathy phase. This entails performing extensive market research to gain insights into the target demographic and choosing a representative reference product that underpins the innovation process. Additionally, the establishment of an interdisciplinary expert team is essential at this juncture, integrating competencies in design, environmental science, and market analysis. It follows that several tools are used to capture multifaceted expectations and motivations in a stakeholder, such as empathy maps, ethnographic interviews, to more sophisticated methodologies like Kansei method. A practitioner should, therefore, provide a mechanism for continuous stakeholder engagement and recognize that customers' and external partners' views will have implications for each subsequent stage.

During the Definition phase, it is necessary that practitioners clearly articulate the objectives of research and the goals concerning design. These objectives should capture both customer needs and priorities on sustainability, as guided by such frameworks as SMART criteria. Also, interpretation of customer expectation into engineering/technical specification is expected to ensure that objectives can be realistic and achievable. In this phase, a design journey is begun, which makes clarity and alignment within an organization's capabilities and sustainability metrics crucially needed. In the Ideation phase, the practitioner develops creative ideas that have the potential to solve the stated problem. The stakeholders should be involved actively, applying techniques such as brainstorming, the QFD method, and the use of a correlation matrix for mapping and prioritizing the customer's criteria. It has to be underlined that the process is iterant, and teams have to be allowed to initially create a wide variety of ideas, then converge into feasible alternatives that are innovative. It supports the collaboration of cross-functional teams to build in considerations for the environment right from the ideation stage.

The prototyping phase involves developing different product prototypes that represent both the current and changed states of product specifications. Professionals should be allowed to use advanced modeling and simulation tools to effectively visualize prototypes, ensuring that each design incorporates customer input in addition to metrics related to environmental sustainability. Prototypes must be evaluated initially by a team of experts to ensure their viability and alignment with organizational goals. This means that it's iterative refinement based on continuous modification brought about by the feedback received and the performance tests conducted. The Testing phase will follow through proper prototype valuation, conducted in accordance with two main assessment criteria: customer satisfaction and environmental impact. Then, the Entropy method, WSM, or FAHP will provide quantification techniques to be applied by practitioners to test the quality of the prototypes regarding their compliance with the life cycle impact benchmark. Testing will utilize customer feedback for further refinement of prototypes to meet the market and sustainability demands. Implementation involves real-word testing environments to confirm the feasibility and desirability for prototyping.

At all stages, there should be openness and full communication on the part of the practitioners. Encouraging active participation by

stakeholders through an ongoing discourse and systematic documentation of decisions, feedback, and evaluation results enhance alignment and accountability. This also opens up avenues for open innovation, where external partners can provide insights into critical knowledge. Besides, practitioners should plan for continuous improvement, using feedback mechanisms to enhance both the product and the design methodology itself. This systematic building of lessons from each iteration enables an organization to be more effective and efficient in its innovation effort. Applications of the model can be greatly enhanced by integrating digital tools and AI capabilities throughout the implementation. AI analytics, visualization tools, and the automation of routine tasks free the practitioner to make strategic decisions while overseeing the complex stakeholder dynamics and sustainability assessments.

These guidelines provide a platform on which professionals can well implement the DT-QLCA model for a harmonious strategy of innovation that would meet customer demands while achieving environmental sustainability objectives.

The DT-QLCA framework is particularly versatile for SMEs or organizations with constrained resources; it offers a structured yet flexible approach to innovation, harmonizing with market requirements and sustainability goals.

Its application can be very broad in business contexts, enabling firms to optimize resource use, improve customer satisfaction, and reduce environmental impact throughout the life cycle of any product. Some examples of specific applications to different industries and resource-constrained environments follow. The DT-QLCA model may drive the redesign of a flagship product in a manufacturing SME company towards reaching new regulatory demands on environmental sustainability while remaining competitive on the marketplace. For instance, a furniture manufacturer might want to use only "green" materials and can use the model to capture customer input on durability and design preference for use in the specification of the product. During the Empathy stage, customer questionnaires and interviews would be directed at expectations about quality and sustainability.

During the Definition phase, this should enumerate goals such as material waste reduced by 20 %, enhanced product recyclability, among others. Prototypes made with various materials-for instance, reclaimed wood or maybe biodegradable composites-can then be tested regarding customer satisfaction and also for life cycle environmental impacts. Iterative prototyping and testing ensure the final product will meet the customer's needs and also meet regulatory requirements, using efficient resources without blowing the budget. The DT-QLCA well describes the balance of innovation against cost in the case of a technology start-up involved in the design of energy-efficient consumer electronics. During the stage of empathy, customer interviews may indicate strong bias for longer life and lesser harm to the environment. These may lead into the definition stage, where objectives of the reduction in carbon footprint by 30 % per device may be defined.

The prototypes would have module designs to enable repair and upgrading to increase life. Testing would be to confirm such designs about quality and environmental standards, involving the customer in the process of feedback and whether or not the product satisfies both functional and ecological standards. The iterative model allows the startup to focus on the minimum number of customer and environmental needs using its limited resources. In this case, in the food and beverage industry, an SME packaged goods manufacturer will employ the DT-QLCA model to renovate its packaging for sustainability. In empathy, customer research indicates the need to cut down on the use of plastic and, simultaneously, be able to have the packing material more recyclable. In the Definition stage, the goals may be to transition into biodegradable materials without jeopardizing the product's freshness and good looks. Thereafter, prototyping can be done on packaging solutions made from materials like biodegradable films or compostable wraps. During Testing, consumers and environmental specialists should be allowed to provide feedback mechanisms in order to improve the

design to verify functionality and ecology standards. By iteration, improvement means that the small and medium-sized enterprise can achieve huge reductions in environmental impact without having to incur disproportionately high expenses. A modest fashion brand may use the DT-QLCA framework to develop an environmentally friendly line of clothes. During the Empathy phase, customer feedback may point to the use of organic fibres and value chain transparency. These observations will be translated into quantifiable targets in the Definition phase, such as sourcing 50 % of the materials from certified organic suppliers. Prototyping can test fabric blends for durability, comfort, and sustainability.

During testing, environmental assessments will quantify the impact of the different supply chain configurations, while consumer feedback makes sure the product meets both form and function criteria. The iterative characteristics of the model, in return, will enable the brand to incrementally improve its products, proving the commitment of sustainability with cost control. Even service-oriented companies and companies with very limited resources, as in a small repair shop, could create added value in order to boost eco-innovation with the DT-QLCA model. For instance, it could design a system of refurbishing and reselling used appliances. During the Empathy stage, the contributions of customers may point out issues related to costs and reliability. The Definition stage will then set goals of minimum e-waste and access to affordable solutions by customers.

Prototypes could involve testing the usability of second-hand appliances and methods of sourcing materials for repairs in a sustainable way. In return, this will validate such processes in terms of customer satisfaction and environmental outcomes, hence helping the business to adopt an eco-friendly model that's scalable.

In all these contexts, DT-QLCA acts to provide a structured method of integrating customer needs and environmental appraisal into product or service design. For SMEs and resource-constrained companies, flexibility and iteration toward refinement ensure that innovation remains feasible and impactful, engendering long-term sustainability and market competitiveness.

5.7. The examples of KPI's which can be used in proposed framework

The KPIs would include important measurements that indicate how DT-QLCA is applied efficiently and, as such, matters very significantly to any company in trying to track and determine one's success (Table 5). These will therefore indicate whether the model would achieve what it should bring on-for instance, bringing customer satisfaction in line with environmental sustainability. Customer Engagement Rate: This refers to the proportion of customers that may be targeted but actually have engaged in providing feedback or getting engaged in co-creative activities. By monitoring this ratio, an organization will make sure its stakeholder insight sources are representative and diverse to anchor informed decisions. The Stakeholder Diversity Index is a measure of the breadth of externals participating, including environmental experts and suppliers. A high diversity index reflects inclusiveness and cooperation, which is requisite in harnessing balanced and creative solutions.

The Objective Alignment Index reflects the degree of alignment between predefined research objectives and corporate sustainability and market objectives. This secures that the foundational stages within the DT-QLCA process are strategically set in such a way that actual progress can be achieved. During the ideation stage, the Ideas to Prototypes Conversion Rate provides a measure of efficiency with regard to transforming generated ideas into actionable prototypes. This is an important metric that helps in demonstrating the effectiveness of the ideation process and ensures that enough ideas are being converted to practical design. Customer Criteria Integration Rate refers to creating prototypes, showing how the customer-identified needs are integrated into design solutions; the underlined responsiveness of feedback to customers in the process assures them that the final products would respond to market demands. While Prototype Iteration Rate expresses the number of

Table 5
Examples of key performance indicators (KPIs) for tracking the effectiveness of the DT-QLCA process.

KPI	Definition	Formula/Measurement	Purpose
Customer Engagement Rate	Percentage of target customers actively participating in feedback activities.	$\frac{\text{Engaged Participants}}{\text{Targeted Participants}} \times 100$	Tracks stakeholder involvement to ensure diverse and meaningful insights.
Stakeholder Diversity Index	Measures variety of external stakeholders (e.g., customers, experts).	Index derived from counts of distinct stakeholder groups involved.	Evaluates inclusivity and collaboration across different perspectives.
Objective Alignment Index	Assesses alignment of defined objectives with sustainability goals.	Qualitative scorecard or alignment index.	Ensures research objectives reflect sustainability and market goals.
Ideas to Prototypes Conversion Rate	Ratio of ideas generated to prototypes developed.	$\frac{\text{Prototypes Developed}}{\text{Ideas Generated}} \times 100$	Monitors the efficiency of the ideation process in generating actionable solutions.
Customer Criteria Integration Rate	Percentage of customer-identified needs incorporated into prototypes.	$\frac{\text{Integrated Customer Criteria}}{\text{Total Identified Criteria}} \times 100$	Tracks responsiveness to customer feedback in the design process.
Prototype Iteration Rate	Number of iterations per prototype before finalization.	Count of iterations per prototype.	Reflects adaptability and refinement in the prototyping phase.
Material Sustainability Index	Measures the eco-friendliness of materials used in prototypes.	Weighted score of metrics such as recyclability, biodegradability, or carbon footprint.	Tracks environmental performance of materials incorporated into designs.
Customer Satisfaction Index	Quantifies customer feedback on prototype performance during testing.	Derived from survey scores or customer ratings (e.g., Likert scale).	Measures alignment of prototypes with user expectations.
Environmental Impact Score	Evaluates the environmental footprint of prototypes based on LCA metrics.	Quantified using indicators like carbon emissions, water use, or energy consumption.	Tracks sustainability outcomes across the product life cycle.
Prototype Success Rate	Percentage of prototypes meeting quality and environmental standards.	$\frac{\text{Successful Prototypes}}{\text{Total Prototypes Tested}} \times 100$	Evaluates overall effectiveness of the prototyping process.
Time-to-Market Efficiency	Measures the duration from project initiation to product launch.	Time in days or weeks from empathy phase to market release.	Tracks process efficiency and responsiveness to market demands.
Resource Utilization Efficiency	Assesses proportion of allocated resources effectively utilized.	$\frac{\text{Resources Utilized}}{\text{Resources Allocated}} \times 100$	Ensures optimal use of time, budget, and materials.
Sustainability Innovation Index	Combines metrics to reflect the overall sustainability impact of the process.	Composite index of reductions in environmental footprint, recyclability, and resource efficiency.	Provides a holistic measure of the eco-innovation achieved.
Market Acceptance Rate	Tracks the market response to the final product.	$\frac{\text{Adopted Products}}{\text{Products Launched}} \times 100$	Measures commercial success and market alignment of the final product.
Continuous Improvement Rate	Evaluates implementation of feedback into future product cycles.	$\frac{\text{Incorporated Feedback Items}}{\text{Total Feedback Items}} \times 100$	Tracks learning and iterative improvement across design cycles.

Source: own elaboration.

iterations a prototype has gone through until being finalized, it shares how adaptable and thorough an innovation will be in its refinement.

Environmental metrics represent an important part of the DT-QLCA, since the Material Sustainability Index indicates if the material used for the prototype is eco-friendly. That would give some indications on the environmental impacts of their choices and whether those were aligned with the idea of sustainability. Environmental performance quantification has been enabled by the provision of an Environmental Impact Score derived from LCA metrics such as carbon and water footprints. This ensures the centrality of environmental concerns in prototype design. Customer Satisfaction Index: This oversees the feedback with regard to prototype performance. This gives the absolute chat of how the design meets or fulfills the expectations of the user. This is supported by Prototype Success Rate: It determines a percentage of prototypes that meet the pre-set benchmarks on quality and the environment directly, which represents effectiveness in prototyping.

Time-to-Market Efficiency: Operational KPIs are those which define the time it takes from the very beginning of the project until the very moment the product is launched, reflecting the agility of the DT-QLCA process. Resource Utilization Efficiency: This is the share of the allocated resources put into effective use to make the best possible use of time, budget, and materials. The Sustainability Innovation Index is an integrated measure that provides a general view about the eco-innovation output of this process, balancing environmental impact against product innovation. This would finally be rounded up with the Market Acceptance Rate for the success in the marketplace and the Continuous Improvement Rate to check the inclusion of feedback into future design cycles. In all, these are key indications that make sure the process not only delivers immediate outcomes but is also nurturing innovation for sustainability in the longer term.

These KPIs will enable the organizations to understand in real-time the real performance of the DT-QLCA model. This enables them to

make evidence-based decisions while continuously improving the approach to achieve better outcomes.

The KPIs selected for a program should account for the most critical processes and functional areas of the company. In our DT-QLCA model, we provided examples (Table 4), but there are established methodologies for integrating LCA and KPIs to assess environmental aspects specific to various industries. Dorn et al. (2016) proposed using key performance indicators (KPIs) enhanced by life cycle assessment (LCA) to evaluate industrial emissions (both direct and indirect), energy intensity, and other sustainability factors in the glass industry. Similarly, Feiz et al. (2015) employed a simplified LCA model based on six key performance indicators to analyze CO2 emissions in the cement industry, a sector also studied by Amrina and Vili (2014). The selection of KPIs and their integration with LCA should align with industry-specific requirements and the environmental aspects being evaluated. Manufacturing companies need a customized measurement framework to accurately assess the parameters involved in the LCA of their products. In the era of Industry 4.0, emerging technologies such as Big Data, Blockchain, IoT, Machine Learning, and additive manufacturing, combined with the digitization of processes, can help companies define and achieve sustainability goals by linking processes with Key Performance Indicators (KPIs) (Contini and Peruzzini, 2022). Numerous studies have already explored the impact of Industry 4.0 technologies on reducing environmental harm. For example, Gajdzik et al. (2021) investigated how innovations in technological processes reduced energy intensity in steel manufacturing. Research areas examining the impact of Industry 4.0 on innovation include responses to new products and innovations, portfolio management, market entry strategies, market exploitation strategies, survival strategies, marketing methods in networked environments, and the complexity of construction and services (Lee et al., 2019; Hauser et al., 2006). For these research domains, our DT-QLCA model may serve as a valuable tool.

5.8. The potential effects of implementation of proposed framework

It gives how the DT-QLCA framework puts together customer-centered innovation and strong environmental assessment as part of doing business with sustainable development considerations in product courses that would always appeal to market demand. The clarification of these implications and their actionable benefits for companies, particularly in cases where resources are scarce or the regulatory and market pressures are rising with regard to sustainable practice, are necessary. Probably one of the most important practical implications of the DT-QLCA framework involves how it can guide decision-making with quantified metrics. By embedding LCA within the design process itself, this framework ensures that every decision in design is based on an understanding of its consequences. This shifts sustainability considerations away from being an afterthought into a central criterion within the innovation process. Companies would be able to make informed decisions on materials, methods of production, and configurations for supply chains, balancing ecological objectives against cost and market feasibility. The framework is customer-oriented, meaning that the product developed will be environmentally viable and also meet the expectations of the consumers. The DT-QLCA model captures subtle insights on user needs, preferences, and pain points through structured stakeholder engagement, including customers. This iterative feedback loop lets companies refine prototypes and develop products that strongly resonate with their target markets, ultimately enhancing product acceptance and customer loyalty. It is with this alignment that businesses see the associated risks of market entry reduce and commercial success increase.

Operationally, it enables efficiency and optimization of resources. The iterative approach of design thinking, coupled with the systematic evaluation from LCA, means companies are able to avoid expensive design mistakes at an early stage. Emphasis on refinement of prototypes reduces waste, with only the most viable designs advanced for production. This is critical for SMEs since they are resource-poor and cannot afford trial-and-error cycles. Adaptability is also given in the level of business scaling of framework application, given available resources, in using it in organizations irrespective of size. The adoption of the DT-QLCA framework strategically affects long-term sustainability and competitive positioning. It allows structured integration of environmental and quality assessments to form an innovative culture in which sustainability is considered a core value, not just a compliance need. This approach will surely meet the growing demand of consumers for greener products but also provide firms with a leading role in sustainable innovation, improving brand reputation and market differentiation.

It also allows for cooperation and openness, important features of the interconnected world of business today. The open innovation part of DT-QLCA enables a company to link with other external parties, like environmental experts, suppliers, and research institutions. This expands the pool of resources and expertise to enable businesses to find innovative and more effective solutions. Transparency in decision-making, based on the quantifiable metrics of LCA, builds trust among customers and regulatory bodies. From a scalability perspective, the DT-QLCA framework provides a means for continuous improvement. This iterative nature of design thinking embeds the lessons learned from each product cycle to feed into the next, hence providing a feedback-driven mechanism toward continued innovation. Companies can use this adaptability to respond to evolving market demands, regulatory changes, and technological advancements, ensuring that their products remain relevant and sustainable over time.

The fact that this framework places much emphasis on matching environmental sustainability with market demand gives companies a dual benefit: reducing the ecological footprint while reaching commercial viability. It is precisely this duality of focus which will make the DT-QLCA model an invaluable strategic tool for business in the modern market, where sustainability and competitive success are inextricably linked with consumer preferences.

The application of DT-QLCA enables the analysis of the impact of product innovations on environmental aspects through Life Cycle Assessment (LCA). Improving the quality of LCA has accelerated the adoption of Industry 4.0 technologies, especially when combined with Open Innovation. Open Innovation enhances product development across various industries (Hizam-Hanafiah and Soomro, 2021; Osorno-Hinojosa et al., 2022; Skordoulis et al., 2020). It has also significantly increased the adoption of Industry 4.0 technologies, particularly in relation to product personalization. The core of a product personalization strategy is the alignment of company activities to continuously deliver greater value to customers. Developing personalized products with new parameters and functionalities requires the integration of Design Thinking and Quality into the LCA process.

6. Conclusion

Sustainable product development is one of the key activities of enterprises that contributes to improving the quality of life in society and reducing negative climate changes. Therefore, there is an increasing observation of efforts by companies towards effective design and improvement of products in a sustainable direction. However, this remains an open issue, especially since traditional design thinking primarily focuses on the customer, while environmental burden issues are often considered a secondary, less significant problem. Consequently, the aim of this article was to develop a design thinking framework focused on seeking eco-innovative product solutions towards their sustainable development. It is assumed that this goal will be achieved by incorporating the QLCA methodology into the design thinking process, which is based on simultaneous, prospective assessment of product prototypes according to their quality and environmental impact throughout their life cycle.

Design thinking and QLCAs could be combined for open innovation processes in sustainable product development, creating an integrated framework that gives equal attention to customer orientation and environmental care at the same time (RQ1). Precisely, this integration starts with embedding QLCA in each stage of the design thinking process: from empathy to definition, ideation, prototyping, and testing. This iterative and user-centered approach of design thinking enables the designers to constantly refine the product concept in light of the customer feedback and QLCA-derived environmental impact metrics, encouraging them further towards the development of solutions balancing innovation with ecological responsibility.

Understanding of the environmental impact concerns likely to be maintained by customers themselves further advances the customer needs and provides a starting platform on which eco-innovative ideas are engendered to meet the market demand. Throughout their development, the QLCA methodology evaluates ideation and prototyping against a set of qualitative criteria, including usability and customer satisfaction, while quantitative measures for resource consumption and emissions are integrated with the life cycle of the product. This would be important in the selection of prototypes that best represent the values of sustainable development and provide an ecological performance innovation pathway without compromise.

QLCA integrated with design thinking fosters open innovation by actively and effectively involving external stakeholders-suppliers, researchers, and sustainability experts-into the core development process of the product. It allows for an open flow of knowledge and ideas among them that encourages diversified insights which may inform and complement design decisions taken by the core team. Besides that, the iterative feedback loops included in design thinking ensure continuous product improvement to meet sustainability goals and rapid adaptations by the teams to changing environmental standards or consumer preferences.

This combined approach, by structuring product development to evaluate both market and environmental criteria at each design thinking stage, will ensure that sustainable product innovations are responsive

not only to the demands of their customers but also proactively minimize environmental impact. This synergy of design thinking and QLCA provides a pragmatic way through which companies can apply open innovations to respond to the twin objectives of customer satisfaction and sustainability.

A DT-QLCA framework enhances decision making in product design by providing structured methodology for the simultaneous consideration of sustainability and customer satisfaction, hence enabling informed choices throughout the design process (RQ2). The framework also embeds QLCA directly in each phase of the DT, allowing decision-makers to analyze the prototypes of products not only with regard to customer-centered quality metrics but also with regard to the environmental impact of the product throughout its whole life cycle. This is a dual approach that ensures the consideration of ecological footprint and usability right from the first steps of design, thus allowing companies to prefer design options that are advanced in both sustainable and user-satisfying aspects. The iterative nature of the DT-QLCA framework allows continuous re-evaluation and fine-tuning of product concepts that would let designers and managers align their decisions with sustainability moving targets without compromising on consumer demands. QLCA metrics provide, for each successive stage in the design process, quantitative information about the environmental consequences of decisions regarding materials, production mode, and other design choices. It therefore provides a more transparent criterion for selecting those options that decrease resource use and waste. This structured decision-making approach goes beyond traditional design thinking in its ability to allow companies to pre-empt and manage trade-offs between customer satisfaction and environmental impact proactively. Eventually, the DT-QLCA framework will have the potential to support organizations in the design of eco-innovative products that meet both market needs and sustainability criteria, hence well-balancing this approach in product design to improve their competitive advantage within an increasingly changing market turned toward responsible and customer-oriented innovation.

The contribution of this paper is basically scientific because it represents a further contribution to integrating principles of sustainable development into innovative product design through the development of an original methodological framework called DT-QLCA. By integrating DT with QLCA, this model will be able to guide organizations in pursuing eco-innovation within product development when it systematically addresses customer needs and environmental concerns early on in the design process. Traditional design approaches may focus on user experience or product functionality, but they do not often specifically examine environmental impact in a methodical manner. What is unique about DT-QLCA is that at every step, it incorporates a dual focus on QLCA. This reflects a gap within sustainable product design, where there is little integration of customer-centered innovation through to rigorous environmental assessments. This model produces creativity in business innovations with ecological responsibility through a structured iterative process that can be adjusted to evolving standards of sustainability and consumers' demands.

The following can be regarded as a novelty in the scientific context of this work: the practical applications of the DT-QLCA framework for research and development, and for industrial contexts, support the development of products that can satisfy user demands with minimum ecological impact. The framework embeds QLCA directly into the design thinking stages and supports real-time assessment of product prototypes based on quality and environmental criteria, providing designers and managers with the possibility to make informed decisions at the earliest possible stage in the design process. This active approach contrasts with more passive methods, in which considerations of sustainability may come later or as an afterthought. Therefore, DT-QLCA encourages decisions on fundamental design and investment questions to be made as early as possible in the design process, in order to avoid the waste of resources and achieve eco-innovation. Hence, this will be highly welcomed in academia and industry for the sound methodology it offers

in a systematic alignment between product design and sustainability objectives, advancing both theoretical research and sustainable design practices.

The novelty of the value of the paper in this context of open innovation lies in its integration of structured and sustainable product design with external collaboration. Embedding QLCA within design thinking, the DT-QLCA framework nurtures open innovation through creating a collaborative environment in which input from various external stakeholders—consumers, suppliers, environmental experts, and research institutions—is systematically integrated at every stage in product development. The innovative process is strengthened by cross-disciplinary sharing of ideas and experience, as organizations may grasp a number of perspectives on environmental impact and customer needs at once. Therefore, the DT-QLCA reinforces the open innovation ecosystem with a structured way of including external contributions in the most transparent manner possible, allowing the development of eco-innovative products closer to market expectations and also in line with sustainability goals. This process highlights the power of transparency and collaboration during product design for sustainability. Indeed, DT-QLCA might be judged as the most significant development of the academic discourse on open innovation in relation to sustainable development.

The research introduces a DT-QLCA-based model that allows companies, especially in research and development (R&D) sectors, to prototype products that simultaneously meet customer demands and minimize environmental harm throughout the product's life cycle. The scientific novelty lies in how the QLCA method balances both qualitative (customer satisfaction) and quantitative (environmental impact) factors in the design process. This method emphasizes decision-making grounded in comprehensive life-cycle evaluations, from the earliest stages of product development, ensuring that eco-innovative solutions are not only technically feasible but also environmentally sustainable.

This work is also valuable for its potential applications in industrial settings, where managers and designers can use the framework to align product development with sustainability goals, driving innovation towards greener practices. The paper thus advances the field by offering a practical tool for operationalizing sustainable development in product design, filling a critical gap in both academic literature and industry practices.

Besides the limitations resulting from results presented above, the proposed framework shows some methodological limitations. The first lies in the simplified approach to assessing the environmental impact of product prototypes, which focuses on a single environmental burden criterion. This narrow focus may overlook other significant environmental factors, leading to a less comprehensive assessment of a product's sustainability. Additionally, the environmental impact analysis relies on modeling with inventory data, which may not always capture the full complexity or real-world variability of environmental outcomes. Another limitation is the requirement for specialized software to conduct life cycle assessments, which may not be readily available or usable by all organizations. Employing various stakeholders as experts in the decision-making process poses the risk of a decision-making bias in product design process and its outcomes. We tried to limit this risk by the intermediate module between Stage 3 and Stage 4 - Evaluating Ideas with MCDM. Employing experts in their respective fields (consumer experts in consumer decisions, suppliers as experts in production, and environmental experts) and using an MCDM methodology tailored to the specific decision problem should significantly reduce the risk of decision-making bias. The flexibility in selecting experts ensures the ease of adapting the model to a specific decision problem, but also gives an opportunity to employ well-informed evaluators, with knowledge specific for one of the decision-making stages – which lowers the risk of bias coming from low level of expertise.

A lack of empirical tests of the model and application guidelines create a potential barrier for widespread adoption of the proposed methodology, particularly for companies lacking the necessary

resources or technical expertise to implement it effectively (Audretsch and Belitski, 2023; Dabić et al., 2023). We are planning to address these limitations in our future research.

In future research, it is essential to supplement and expand the proposed framework to ensure the search for eco-innovative product solutions while considering other key sustainability criteria, such as investment costs in product development. We are planning to improve the methodology for prospective assessment of the environmental impact of product prototypes to ensure the analysis of not just one, but multiple environmental burden criteria. Additionally, empirical tests of the proposed model, together with a step-by-step application procedure are worth a separate research and publication. Considering the generally low wish of SMEs managers to employ scientific MCDM tools in their decision-making, we believe that a separate reasoning needs to be developed to make our model easily accessible for these type of companies. Replacing at least some expert groups by the Artificial Intelligence (AI) could also be an interesting, but today still future area of research. Developing a standardized KPI-based metric of achieved changes in sustainability could offer a clear and measurable metric for comparison, prediction and planning purposes. Finally, researching the possibilities of integrating our proposition of DT-QLCA with the FMEA framework by Spreafico and Sutrisno (2023) is a promising direction for further research.

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Ethical statement

Hereby, I /Radosław Wolniak/ consciously assure that for the manuscript /insert title/ the following is fulfilled:

- 1) This material is the authors' own original work, which has not been previously published elsewhere.
- 2) The paper is not currently being considered for publication elsewhere.
- 3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
- 4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
- 5) The results are appropriately placed in the context of prior and existing research.
- 6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
- 7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement

Dominika Siwiec: Writing – original draft. **Bożena Gajdzik:** Writing – original draft. **Andrzej Pacana:** Writing – original draft. **Radosław Wolniak:** Writing – original draft. **Remigiusz Gawlik:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Al Nuaimi, F.M.S., Singh, S.K., Ahmad, S.Z., 2024. Open innovation in SMEs: a dynamic capabilities perspective. *J. Knowl. Manag.* 28 (2), 484–504. <https://doi.org/10.1108/JKM-11-2022-0906>.
- Alaniz-Munoz, J.L., Rodriguez-Verduzco, J.L., Ahumada-Tello, E., Barragan-Quintero, R. V., 2023. RF design through open innovation, design thinking, and FODA analysis: an innovative application, 1st IEEE Colombian Caribbean Conference, C3 2023.
- Amrina, E., Vilsı, A.L., 2014. Interpretive structural model of key performance indicators for sustainable manufacturing evaluation in cement industry, In Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, Selangor, Malaysia, 9–12 December 2014; pp. 1111–1115.
- An, J., Mikhaylov, A., 2024. Technology-based forecasting approach for recognizing trade-off between time-to-market reduction and devising a scheduling process in open innovation management. *J. Open Innov. Technol. Mark. Complex.* 10 (1), 100207. <https://doi.org/10.1016/j.joitmc.2024.100207>.
- Appleyard, M.M., Velazquez, H., 2024. Customer-centric open innovation guided by design strategy. *Oxf. Handb. Open Innov.* 640–652.
- Aris, N.Md, Ibrahim, N.H., Halim, N.D.A., 2025. Design and development research (DDR) approach in designing design thinking chemistry module to empower students' innovation competencies. *J. Adv. Res. Appl. Sci. Eng. Technol.* 44 (1), 55–68.
- Asad, M., Asif, M.U., Sulaiman, M.A.B.A., Satar, M.S., Alarifi, G., 2023. Open innovation: the missing nexus between entrepreneurial orientation, total quality management, and performance of SMEs. *J. Innov. Entrep.* 12, 79. <https://doi.org/10.1186/s13731-023-00335-7>.
- Audretsch, B.D., Belitski, M., 2023. The limits to open innovation and its impact on innovation performance. *Technovation* 119, 102519. <https://doi.org/10.1016/j.technovation.2022.102519>.
- Bajdur, W.M., 2021. Eco-innovation in chemical technologies – examples of lca applications. *Przemysł Chem.* 100 (11), 1120–1122.
- Balazińska, M., Markowska, M., Blaut, A., Godniok, M., 2020. Life cycle assessment of eco-innovative organo-mineral granulated fertilizer's production technology, *Rocznik. Ochr. Srodowiska* 22 (1), 561–588.
- Bartar, P., 2023. Knowledge production with design thinking for citizen science. *Proc. Sci.* 023.
- Batwara, A., Sharma, V., Makkar, M., Giallanza, A., 2022. An empirical investigation of green product design and development strategies for eco industries using Kano model and Fuzzy AHP. *Sustainability* 14 (14), 8735. <https://doi.org/10.3390/su14148735>.
- Beaudoin, C., Joncoux, S., Jasmin, J.-F., Schillo, R.S., Nguyen, V.M., 2022. A research agenda for evaluating living labs as an open innovation model for environmental and agricultural sustainability. *Environ. Chall.* 7, 100505.
- Bender-Salazar, R., 2023. Design thinking as an effective method for problem-setting and need finding for entrepreneurial teams addressing wicked problems. *J. Innov. Entrep.* 12 (1), 24.
- Berthelot, A., Caron, E., Jay, M., Lefèvre, L., 2024. Estimating the environmental impact of Generative-AI services using an LCA-based methodology. *Procedia CIRP* 122, 707–712.
- Beverland, M.B., Wilner, S.J.S., Micheli, P., 2015. Reconciling the tension between consistency and relevance: design thinking as a mechanism for brand ambidexterity. *J. Acad. Mark. Sci.* 43 (5), 589–609. <https://doi.org/10.1007/s11747-015-0443-8>.
- Bigliardi, B., Filippelli, S., 2022. Sustainability and open innovation: main themes and research trajectories. *Sustainability* 14, 6763. <https://doi.org/10.3390/su14116763>.
- Birkeland, J., 2022. Nature positive: interrogating sustainable design frameworks for their potential to deliver eco-positive outcomes. *Urban Sci.* 6 (2), 35. <https://doi.org/10.3390/urbansci6020035>.
- Bocken, N.M.P., Rana, P., Short, S.W., 2015. Value mapping for sustainable business thinking. *J. Ind. Prod. Eng.* 32 (1), 67–81. <https://doi.org/10.1080/21681015.2014.1000399>.
- Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. *J. Clean. Prod.* 65, 42–56. <https://doi.org/10.1016/j.jclepro.2013.11.039>.
- Bonini, L.A., Sbragia, R., 2011. O Modelo de Design Thinking como Indutor da Inovação nas Empresas: Um Estudo Empírico. *Rev. De. Gest. ão e Proj.* 2 (1), 03–25. <https://doi.org/10.5585/gep.v2i1.36>.
- Boons, F., Montalvo, C., Quist, J., Wagner, M., 2013. Sustainable innovation, business models and economic performance: an overview. *J. Clean. Prod.* 45, 1–8. <https://doi.org/10.1016/j.jclepro.2012.08.013>.
- Brodnicki, K., 2015. Application of design thinking approach in functioning of enterprises [Zastosowanie koncepcji design thinking w funkcjonowaniu przedsiębiorstw]. *Przedsiębiorstwo We Współczesnej Gospod. Teor. i Prakt.* 4 (15), 35–45.
- Carhuacusma, C.A.C., Ovalle, C. (2023). Framework Based on BPM and Design Thinking to Optimize the Monitoring and Control Process in the Area of Project Quality | Framework basado en BPM y Design thinking para optimizar el proceso de seguimiento y control en el área de calidad de proyectos, Proceedings of the LACCEI international Multi-conference for Engineering, Education and Technology, 2023-July.

- Carrasco-Carvajal, O., García-Pérez-de-Lema, D., Castillo-Vergara, M., 2023. Impact of innovation strategy, absorptive capacity, and open innovation on SME performance: a Chilean case study. *J. Open Innov. Technol. Mark. Complex.* 9 (2), 100065.
- Castiblanco Jimenez, I.A., Mauro, S., Napoli, D., Marcolin, F., Vezzetti, E., Rojas Torres, M.C., Specchia, S., Moos, S., 2021. Design thinking as a framework for the design of a sustainable waste sterilization system: the case of Piedmont Region, Italy. *Electronics* 10 (21), 2665. <https://doi.org/10.3390/electronics10212665>.
- Chen, S., Venkatesh, A., 2013. An investigation of how design-oriented organisations implement design thinking. *J. Mark. Manag.* 29 (15–16), 1680–1700. <https://doi.org/10.1080/0267257X.2013.800898>.
- Ching, N.T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., Asadi, S., 2022. Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development. *J. Clean. Prod.* 334, 130133. <https://doi.org/10.1016/j.jclepro.2021.130133>.
- Chu, Y.-Y., Liu, K.-H., 2023. Managing open innovation challenges: implementing organizational ambidextrous as a managerial approach. *AIP Conf. Proc.* 2685, 040019.
- Cirule, I., Uvarova, I., 2022. Open innovation and determinants of technology-driven sustainable value creation in incubated start-ups. *J. Open Innov. Technol. Mark. Complex.* 8, 162. <https://doi.org/10.3390/joitmc8030162>.
- Contini, G., Peruzzini, M., 2022. Sustainability and Industry 4.0: definition of a set of key performance indicators for manufacturing companies. *Sustainability* 14, 11004. <https://doi.org/10.3390/su141711004>.
- Costa, A., Crupi, A., De Marco, C.E., Di Minin, A., 2023. SMEs and open innovation: challenges and costs of engagement. *Technol. Forecast. Soc. Change* 194, 122731. <https://doi.org/10.1016/j.techfore.2023.122731>.
- da Costa Junior, J., Diehl, J.C., Snelders, D., 2019. A framework for a systems design approach to complex societal problems. *Des. Sci.* 5, e2. <https://doi.org/10.1017/dsj.2018.16>.
- Dabić, M., Daim, T., Bogers, M.L.A.M., Mention, A.-L., 2023. The limits of open innovation: failures, risks, and costs in open innovation practice and theory. *Technovation* 126, 102786.
- De Angelis, R., Ianulardo, G., 2024. Circular economy principles as a basis for a sustainability management theory: a systems thinking and moral imagination approach. *Bus. Strategy Environ.* 33 (5), 4861–4870.
- DeWaters, J., Kotla, B., 2023. Using an open-ended socio-technical design challenge for entrepreneurship education in a first-year engineering course. *Front. Educ.* 8, 1198161.
- Dewberry, E.L., de Barros, M.M., 2009. Exploring the need for more radical sustainable innovation: what does it look like and why? *Int. J. Sustain. Eng.* 2 (1), 28–39. <https://doi.org/10.1080/19397030802643518>.
- Diepenmaat, H., Kemp, R., Velter, M., 2020. Why sustainable development requires societal innovation and cannot be achieved without this. *Sustainability* 12 (3), 1270. <https://doi.org/10.3390/su12031270>.
- Dilip, M., Kerr, M.E., 2024. Circles of sustainability: an activity for visualizing synergies and trade-offs in a systems thinking environment. *Green. Chem. Lett. Rev.* 17 (1), 2381596.
- Elsbach, K.D., Stigliani, I., 2019. The physical work environment and creativity: How creative workspaces support and encourage design thinking. *Organizational Behaviour and the Physical Environment*. pp. 13–36.
- Fabrizi, A., Guarini, G., Meliciani, V., 2023. The impact of the open eco-innovation mode on employment: the case of Italian network business agreements. *Handb. Innov., Soc. Environ.* 67–83.
- Faludi, J., Agogino, A.M., 2018. What design practices do professionals use for sustainability and innovation. *Proceedings of International Design Conference, 6DESIGN26332644*.
- Faridzad, A.M., Naghizadeh, M., Ghazinoori, S., Mirvahedi, S., 2024. Redefining the innovation capacity of design thinking approach through in-depth understanding of designerly capabilities. *Int. J. Innov. Technol. Manag.* 21 (3), 2450017.
- Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A., Marshall, R., 2015. Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. *J. Clean. Prod.* 98, 272–281. <https://doi.org/10.1016/j.jclepro.2014.01.083>.
- Ferlito, R., Faraci, R., 2022. Business model innovation for sustainability: a new framework. *Innov. Manag. Rev.* 19 (3), 222–236. <https://doi.org/10.1108/INMR-07-2021-0125>.
- Fern, E., 1982. The use of focus groups for idea generation: the effects of group size, acquaintanceship, and moderator on response quantity and quality. *J. Mark. Res.* 19 (1), 1–13.
- Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* 11 (2), 80–85. <https://doi.org/10.1065/lca2006.02.002>.
- Gajdzik, B., 2022. Frameworks of the maturity model for industry 4.0 with assessment of maturity levels on the example of the segment of steel enterprises in Poland. *June 2022 J. Open Innov. Technol. Mark. Complex.* 8 (2), 77. <https://doi.org/10.3390/joitmc8020077>.
- Gajdzik, B., Jaciow, M., Wolny, R., 2023. Types of E-consumers and their implications for sustainable consumption—a study of the behavior of Polish E-consumers in the second decade of the 21st century. *Sustainability* 15, 12647. <https://doi.org/10.3390/su151612647>.
- Gajdzik, B., Siwiec, D., Wolniak, R., Pacana, A., 2024a. Approaching open innovation in customization frameworks for product prototypes with emphasis on quality and life cycle assessment (QLCA). *J. Open Innov. Technol. Mark. Complex.* 10 (2), 100268. <https://doi.org/10.1016/j.joitmc.2024.100268>.
- Gajdzik, B., Sroka, W., Vveinhardt, J., 2021. Energy intensity of steel manufactured utilising EAF technology as a function of investments made: the case of the steel industry in Poland. *Energies* 14, 5152. <https://doi.org/10.3390/en14165152>.
- Gajdzik, B., Wolniak, R., 2021. Digitalisation and Innovation in the Steel Industry in Poland—Selected Tools of ICT in an Analysis of Statistical Data and a Case Study. *Energies* 14, 3034.
- Gajdzik, B., Wolniak, R., Grebski W., Szyszal, J., & Grebski E.M. (2025). *Sustainability and Smart Manufacturing. The Transformation of the Steelwork Industry*. Routledge (book).
- Gajdzik, B., Wolniak, R., 2022b. Framework for R&D&i activities in the steel industry in popularizing the idea of industry 4.0. *J. Open Innov. Technol. Mark. Complex.* 8, 133. <https://doi.org/10.3390/joitmc8030133>.
- Gajdzik, B., Wolniak, R., 2022a. Smart production workers in terms of creativity and innovation: the implication for open innovation. *J. Open Innov. Technol. Mark. Complex.* 8, 68. <https://doi.org/10.3390/joitmc8020068>.
- Gajdzik, B., Wolniak, R., 2022c. Influence of Industry 4.0 projects on business operations: literature and empirical pilot studies based on case studies in Poland. *J. Open Innov. Technol. Mark. Complex.* 8, 44. <https://doi.org/10.3390/joitmc8010044>.
- Gawlik, R., 2008. Preliminary criteria reduction for the application of analytic hierarchy process method. In: Fuxman, L., Delener, N., Lu, V., Rivera-Solis, L. (Eds.), *Evolution and Revolution in the Global Economy: Enhancing Innovation and Competitiveness Worldwide*. Global Business and Technology Association, New York, pp. 366–374.
- Gawlik, R., Siwiec, D., Pacana, A., 2024. Quality–cost–environment assessment of sustainable manufacturing of photovoltaic panels. *Energies* 17 (7), 1522. <https://doi.org/10.3390/en17071522>.
- Geissdoerfer, M., Bocken, N.M.P., Hultink, E.J., 2016. Design thinking to enhance the sustainable business modelling process – a workshop based on a value mapping process. *J. Clean. Prod.* 135, 1218–1232. <https://doi.org/10.1016/j.jclepro.2016.07.020>.
- Giardino, P.L., Cristofaro, M., Marullo, C., 2023. Managing open innovation projects: an evidence-based framework for SMEs and large companies cooperation. *Manag. Res. Rev.* 46 (8), 1163–1183.
- Go, T.F., Wahab, D.A., Hishamuddin, H., 2016. Evaluation of eco-design strategies for development of multiple life-cycle products. *Int. J. Automot. Mech. Eng.* 13 (3), 3642–3656. <https://doi.org/10.15282/ijame.13.3.2016.9.0299>.
- Gonçalves, R., Vlačić, B., González-Loureiro, M., Sousa, R., 2024. The impact of open innovation on the environmental sustainability practices and international sales intensity nexus: a multicountry study. *Int. Bus. Rev.* 33 (5), 102279.
- Gong, X., Guo, Z., Xie, Z., 2022. Using Kansei engineering for the design thinking framework: bamboo pen holder product design. *Sustainability* 14 (17), 10556. <https://doi.org/10.3390/su141710556>.
- Gyamfi, S., Sein, Y.Y., 2021. Determinants of sustainable open innovations—a firm-level capacity analysis. *Sustainability* 13, 9088. <https://doi.org/10.3390/su13169088>.
- Halvorsen, K., 2013. Team decision making in the workplace. *J. Appl. Linguist. Prof. Pract.* 7 (3), 273–296. <https://doi.org/10.1558/japl.v7i3.273>.
- Hauser, J., Tellis, G.J., Griffin, A., 2006. Research on innovation: a review and agenda. *Mark. Sci.* 25, 687–717.
- Hawryszkiewicz, I., Alqahtani, A. (2020). Integrating open innovation process with the double diamond design thinking model. *Proceedings of the European Conference on Knowledge Management, ECKM, 2020-December*, pp. 1003–1006.
- Hizam-Hanafiah, M., Soomro, M.A. (2021). The situation of technology companies in industry 4.0 and the open innovation. *J. Open Innov.* 7, 34.
- Hoolohan, C., Browne, A.L., 2020. Design thinking for practice-based intervention: Co-producing the change points toolkit to unlock (un)sustainable practices. *Des. Stud.* 67, 102–132. <https://doi.org/10.1016/j.destud.2019.12.002>.
- Huong, P.T., Cherian, J., Hien, N.T., Sial, M.S., Samad, S., Tuan, B.A., 2021. Environmental management, green innovation, and social-open innovation. *J. Open Innov.: Technol., Mark., Complex.* 7 (1), 89. <https://doi.org/10.3390/joitmc7010089>.
- Hyman, M., Sierra, J., 2016. Selecting a sample size for your customer survey. *Bus. Outlook* 14 (5), 1–5.
- Kayyali, M., 2024. Design thinking and creativity in entrepreneurial innovation. *Appl. Bus. Intell. Innov. Entrep.* 155–170.
- Kim, B.-Y., Oh, H., 2001. An extended application of importance-performance analysis. *J. Hosp. Leis. Mark.* 9 (3–4), 107–125. https://doi.org/10.1300/J150v09n03_08.
- Kim, Y., Roh, T., Boroumand, R.H., 2024. Resource recombination perspective on open eco-innovation: Open innovation type, strategic orientation, and green innovation. *Bus. Strategy Environ.* 33 (7), 6207–6220.
- Kiseleva, O.N., Syssoeva, O.V., Vasina, A.V., Syssoev, V.V., 2022. Updating the open innovation concept based on ecosystem approach: regional aspects. *J. Open Innov. Technol. Mark. Complex.* 8, 103. <https://doi.org/10.3390/joitmc8020103>.
- Kolman, R., 1992. *Quality Engineering*. PWE.
- Kozłowski, A., Searcy, C., & Bardecki, M. (2016). Innovation for a Sustainable Fashion Industry: A Design Focused Approach Toward the Development of New Business Models (pp. 151–169). https://doi.org/10.1007/978-981-10-0245-8_5.
- Kratzer, J., Meissner, D., Roud, V., 2017. Open innovation and company culture: internal openness makes the difference. *Technol. Forecast. Soc. Change* 119, 128–138. <https://doi.org/10.1016/j.techfore.2017.03.022>.
- Krueger, R.A., 2014. *Focus Group: A Pract. Guide Appl. Res.*, Sage Publ.
- Kupraszewicz, W., Zóltowski, B., 2002. Dobór zespołu ekspertów do diagnozowania stanu maszyn [The selection of the experts team to diagnose the condition of the machines]. *Diagnostyka* 26, 94–100.
- Kwong, C.K., Bai, H., 2002. A fuzzy AHP approach to the determination of importance weights of customer requirements in quality function deployment. *J. Intell. Manuf.* 13 (5), 367–377. <https://doi.org/10.1023/A:1019984626631>.

- Lamnatou, C., Cristofari, C., Chemisana, D., 2024. Artificial Intelligence (AI) in relation to environmental life-cycle assessment, photovoltaics, smart grids and small-island economies. *Sustain. Energy Technol. Assess.* 71, 104005.
- Langhans, S.D., Reichert, P., Schuwirth, N., 2014. The method matters: a guide for indicator aggregation in ecological assessments. *Ecol. Indic.* 45, 494–507. <https://doi.org/10.1016/j.ecolind.2014.05.014>.
- Lawor, B., Hornyak, M., 2012. Smart goals: how the application of smart goals can contribute to achievement of student learning outcomes. *Dev. Bus. Simul. Exp. Learn.* 39, 259–267.
- Leão, C.P., Silva, V., Costa, S., 2024. Exploring the intersection of ergonomics, design thinking, and AI/ML in design innovation. *applied system innovation*, 7 (4), 65.
- Lee, M.-J., Roh, T., 2023. Unpacking the sustainable performance in the business ecosystem: coopetition strategy, open innovation, and digitalization capability. *J. Clean. Prod.* 412, 137433. <https://doi.org/10.1016/j.jclepro.2023.137433>.
- Li, W.-T., Ho, M.-C., Yang, C., 2019. A design thinking-based study of the prospect of the sustainable development of traditional handicrafts. *Sustainability* 11 (18), 4823. <https://doi.org/10.3390/su11184823>.
- Li, Y., Li, L., Wu, Z., 2024. How to benefit from open innovation? The moderating effect of open culture and open organization. *IEEE Trans. Eng. Manag.* 71, 5129–5142.
- Li, W., Wang, J., Chen, R., Xi, Y., Liu, S.Q., Wu, F., Masoud, M., Wu, X., 2019. Innovation-driven industrial green development: the moderating role of regional factors. *J. Clean. Prod.* 222, 344–354.
- Liedtka, J., 2014. Innovative ways companies are using design thinking. *Strategy Leadersh.* 42 (2), 40–45. <https://doi.org/10.1108/SL-01-2014-0004>.
- Liedtka, J., 2020. Putting technology in its place: design thinking's social technology at work. *Calif. Manag. Rev.* 62 (2), 53–83. <https://doi.org/10.1177/0008125619897391>.
- Liedtka, J., Kaplan, S., 2019. How design thinking opens new frontiers for strategy development. *Strategy Leadersh.* 47 (2), 3–10. <https://doi.org/10.1108/SL-01-2019-0007>.
- Lippolis, S., Ruggieri, A., Leopizzi, R., 2023. Open Innovation for sustainable transition: the case of Enel open power. *Bus. Strategy Environ.* 32, 4202–4216. <https://doi.org/10.1002/bse.3361>.
- Liu, W., He, Q., Cao, J., Kamar, A., 2024. Exploring the catalysts of eco-innovation: Employee ownership and sustainable practices. *Technol. Forecast. Soc. Change* 207, 123629.
- Loderer, M., Kock, A., 2021. The influence of design thinking on open innovation. *Int. J. Innov. Manag.* 25 (10), 2140001.
- Luotola, H., Hellström, M., Gustafsson, M., Perminova-Harikoski, O., 2017. Embracing uncertainty in value-based selling by means of design thinking. *Ind. Mark. Manag.* 65, 59–75. <https://doi.org/10.1016/j.indmarman.2017.05.004>.
- Maher, R., Maher, M., Mann, S., McAlpine, C.A., 2018. Integrating design thinking with sustainability science: a research through design approach. *Sustain. Sci.* 13 (6), 1565–1587. <https://doi.org/10.1007/s11625-018-0618-6>.
- Marullo, C., Shapira, P., Di Minin, A., 2024. Enhancing SME innovation across European regions: success factors in EU-funded open innovation networks. *Technol. Forecast. Soc. Change* 201, 123207.
- Matthews, N.E., Stamford, L., Shapira, P., 2019. Aligning sustainability assessment with responsible research and innovation: towards a framework for constructive sustainability assessment. *Sustain. Prod. Consum.* 20, 58–73. <https://doi.org/10.1016/j.spc.2019.05.002>.
- McGuckin, S., Su, N., Abhari, K., 2022. The limits of open innovation: a literature review and research agenda. *Proc. Annu. Hawaii Int. Conf. Syst. Sci.* 5628–5637, 2022-January.
- Mehdipour, Z., 2024. The application of AI for electronic LCA data and assessment toward the circular economy, International Conference Electronics Goes Green 2024 + : From Silicon to Sustainability, EGG 2024 - Proceedings.
- Meidute-Kavaliauskiene, I., Čiğdem, Ş., Vasilis Vasiliauskas, A., Yıldız, B., 2021. Green innovation in environmental complexity: the implication of open innovation. *J. Open Innov. Technol. Mark. Complex.* 7 (2), 107. <https://doi.org/10.3390/joitmc7020107>.
- Meinel, C., Krohn, T., 2022. Design thinking in education: innovation can be learned, design thinking in education. *Innov. Can. Be Learn.* 1–290.
- Memon, M.A., Ting, H., Cheah, J.-H., Thurasamy, R., Chuah, F., Cham, T.H., 2020. Sample size for survey research: review and recommendations. *J. Appl. Struct. Equ. Model.* 4 (2). [https://doi.org/10.47263/JASEM.4\(2\)01](https://doi.org/10.47263/JASEM.4(2)01).
- Micheli, P., Wilner, S.J.S., Bhatti, S.H., Mura, M., Beverland, M.B., 2019. Doing design thinking: conceptual review, synthesis, and research agenda. *J. Prod. Innov. Manag.* 36 (2), 124–148. <https://doi.org/10.1111/jpim.12466>.
- Mu, E., & Pereyra-Rojas, M. (2017). *Practical Decision Making* (1st ed., Vol. 1). Springer International Publishing. <https://doi.org/10.1007/978-3-319-33861-3>.
- Munodawafa, R.T., Johl, S.K., 2024. Exploring eco-innovation capability and operational performance of energy service companies: Does ownership structure make a difference? *Bus. Strategy Dev.* 7 (3), e70010.
- Nagaraj, V., Berente, N., Lyytinen, K., Gaskin, J., 2020. Team design thinking, product innovativeness, and the moderating role of problem unfamiliarity. *J. Prod. Innov. Manag.* 37 (4), 297–323. <https://doi.org/10.1111/jpim.12528>.
- Nakata, C., 2020. Design thinking for innovation: considering distinctions, fit, and use in firms. *Bus. Horiz.* 63 (6), 763–772. <https://doi.org/10.1016/j.bushor.2020.07.008>.
- Nilsson, F., Göransson, M., 2021. Critical factors for the realization of sustainable supply chain innovations - model development based on a systematic literature review. *J. Clean. Prod.* 296, 126471. <https://doi.org/10.1016/j.jclepro.2021.126471>.
- Nyumba, T.O., Wilson, K., Derrick, C.J., Mukherjee, N., 2018. The use of focus group discussion methodology: insights from two decades of application in conservation. *Methods Ecol. Evol.* 9 (1), 20–32. <https://doi.org/10.1111/2041-210X.12860>.
- Oliveira, J., Rua, O.L., 2024. Innovation ecosystems and open innovation on micro-enterprises. *J. Open Innov. Technol. Mark. Complex.*, 100443 <https://doi.org/10.1016/j.joitmc.2024.100443>.
- Osomo-Hinojosa, R., Koria, M., Ramirez-Vasquez, D.C., 2022. Open Innovation with value co-creation from University–industry collaboration. *J. Open Innov. Technol. Mark. Complex.* 8, 32.
- Pacana, A., Siwiec, D., Bednářová, L., Petrovský, J., 2023. Improving the process of product design in a phase of life cycle assessment (LCA). *Processes* 11, 2579. <https://doi.org/10.3390/pr11092579>.
- Pacana, A., Siwiec, D., 2021. Universal model to support the quality improvement of industrial products. *Materials* 14 (24), 7872. <https://doi.org/10.3390/ma14247872>.
- Petit-Boix, A., Arnal, C., Marín, D., Gabarrell, X., Rieradevall, J., 2018. Addressing the life cycle of sewers in contrasting cities through an eco-efficiency approach. *J. Ind. Ecol.* 22 (5), 1092–1104.
- Plugmann, P., 2024. Academics' willingness to participate in an open innovation healthcare and life science ecosystem platform outside their qualifications and working experience (Follow-Up Study). *Manag. Prof.* 261–272. Part F2525.
- Ponto, J., 2015. Understanding and evaluating survey research. *J. Adv. Pract. Oncol.* 6 (2), 168–171.
- Prospe, M., Finkbeiner, M., 2020. Obsolescence in LCA—methodological challenges and solution approaches. *Int. J. Life Cycle Assess.* 25 (3), 495–507. <https://doi.org/10.1007/s11367-019-01710-x>.
- Putman, V.L., Paulus, P.B., 2009. Brainstorming, brainstorming rules and decision making. *J. Creat. Behav.* 43 (1), 29–40. <https://doi.org/10.1002/j.2162-6057.2009.tb01304.x>.
- Pyökkö, H., Suoheimo, M., Walter, S., 2021. Approaching sustainability transition in supply chains as a wicked problem: systematic literature review in light of the evolved double diamond design process model. *Processes* 9 (12), 2135. <https://doi.org/10.3390/pr9122135>.
- Radziwon, A., Vanhaverbeke, W., 2024. Open innovation in small and medium-sized enterprises. *The Oxford Handbook of Open Innovation*. Oxford University Press, pp. 119–139. <https://doi.org/10.1093/oxfordhb/9780192899798.013.8>.
- Renaud, M., Sarrazin, A., Lopes-Barbosa, J., Servin, I., Boulard, F., 2024. Life Cycle Assessment of etching processes for FDSOI transistors technologies. *Proceedings of SPIE - The International Society for Optical Engineering* 12958129580K.
- Robbins, P., 2018. From design thinking to art thinking with an open innovation perspective—a case study of how art thinking rescued a cultural institution in Dublin. *J. Open Innov. Technol. Mark. Complex.* 4 (4), 57.
- Roh, T., Xiao, S.S., Park, B.I., 2023. Effects of open innovation on eco-innovation in meta-organizations: evidence from Korean SMEs. *Asian Bus. Manag.* 22 (5), 2004–2028.
- Romero-Rodríguez, J.-M., Ramírez-Montoya, M.-S., Aznar-Díaz, I., Hinojo-Lucena, F.-J., 2020. Social appropriation of knowledge as a key factor for local development and open innovation: a systematic review. *J. Open Innov. Technol. Mark. Complex.* 6 (2), 44. <https://doi.org/10.3390/joitmc6020044>.
- Rösch, N., Tiberius, V., Kraus, S., 2023. Design thinking for innovation: context factors, process, and outcomes. *Eur. J. Innov. Manag.* 26 (7), 160–176. <https://doi.org/10.1108/EJIM-03-2022-0164>.
- Sakao, T., 2007. A QFD-centred design methodology for environmentally conscious product design. *Int. J. Prod. Res.* 45 (18–19), 4143–4162. <https://doi.org/10.1080/00207540701450179>.
- Sala, S., 2020. Eco-innovation options in food processing. *Environ. Sustain. Mater.* 1 (5), 358–362, 1–5.
- Saniuk, S., Grabowska, S., Gajdzik, B., 2020. Personalization of products in the industry 4.0 concept and its impact on achieving a higher level of sustainable consumption. *Energies* 13, 5895. <https://doi.org/10.3390/en13225895>.
- Santa-Maria, T., Vermeulen, W.J.V., Baumgartner, R.J., 2022. The circular sprint: circular business model innovation through design thinking. *J. Clean. Prod.* 362, 132323. <https://doi.org/10.1016/j.jclepro.2022.132323>.
- Sarango-Lalangui, P., Castillo-Vergara, M., Carrasco-Carvajal, O., Durendez, A., 2023. Impact of environmental sustainability on open innovation in SMEs: an empirical study considering the moderating effect of gender. *Heliyon* 9 (9), e20096.
- Schraven, D.F.J., Arghandeh Jouneghani, P., Jonkers, H.M., Hertogh, M.J.C.M., 2023. Design to market thinking: exploring the merits of strategic niche management in design thinking. *Technol. Anal. Strateg. Manag.* 35 (6), 767–784. <https://doi.org/10.1080/09537325.2021.1986211>.
- Seidel, V.P., Fixson, S.K., 2013. Adopting design thinking in novice multidisciplinary teams: the application and limits of design methods and reflexive practices. *J. Prod. Innov. Manag.* 30 (S1), 19–33. <https://doi.org/10.1111/jpim.12061>.
- Sever, I., 2015. Importance-performance analysis: a valid management tool? *Tour. Manag.* 48, 43–53. <https://doi.org/10.1016/j.tourman.2014.10.022>.
- Shen, Y., Zhou, J., Pantelous, A.A., Liu, Y., Zhang, Z., 2022. A voice of the customer real-time strategy: an integrated quality function deployment approach. *Comput. Ind. Eng.* 169, 108233. <https://doi.org/10.1016/j.cie.2022.108233>.
- Siwiec, D., Pacana, A., 2021. A pro-environmental method of sample size determination to predict the quality level of products considering current customers' expectations. *Sustainability* 13 (10), 5542. <https://doi.org/10.3390/su13105542>.
- Siwiec, D., Pacana, A., 2024. Eco-innovation method for sustainable development of energy-producing products considering quality and life cycle assessment (QLCA). *Energies* 17 (15), 3841. <https://doi.org/10.3390/en17153841>.
- Skordoulis, M., Ntanos, S., Kyriakopoulos, G.L., 2020. Environmental innovation, open innovation dynamics and competitive advantage of medium and large-sized firms. *J. Open Innov. Technol. Mark. Complex.* 6, 195.
- Sondhi, S.S., Salwan, P., Niranjan, S., Hawkins, T., Behl, A., Pereira, V., del Giudice, M., 2024. Exploring open innovation dynamics: service and delivery interplay in circular economy. *IEEE Trans. Eng. Manag.* 71, 15511–15524. <https://doi.org/10.1109/TEM.2024.3483750>.

- Soomro, S.A., Casakin, H., Georgiev, G.V., 2021. Sustainable design and prototyping using digital fabrication tools for education. *Sustainability* 13 (3), 1196. <https://doi.org/10.3390/su13031196>.
- Spinnewijn, L., Aarts, J.W.M., Braat, D., Scheele, F., 2024. Unravelling clinicians' shared decision-making adoption: a qualitative exploration through the lens of diffusion of innovations theory. *BMJ Open* 14 (6), e080765.
- Spreafico, C., Sutrisno, A., 2023. Artificial intelligence assisted social failure mode and effect analysis (FMEA) for sustainable product design. *Sustainability* 15, 8678. <https://doi.org/10.3390/su15118678>.
- Sullivan, G.M., Artino, A.R., 2013. Analysing and interpreting data from likert-type scales. *J. Grad. Med. Educ.* 5 (4), 541–542. <https://doi.org/10.4300/JGME-5-4-18>.
- Svirina, A., Zabbarova, A., Oganisjana, K., 2016. Implementing open innovation concept in social business. *J. Open Innov. Technol. Mark. Complex.* 2 (4), 1–10. <https://doi.org/10.1186/s40852-016-0046-8>.
- Tabrizi, T.B., Gocer, O., Sadrieh, A., Globa, A., 2023. Leveraging AI to instruct architecture students on circular design techniques and life cycle assessment. *Int. Conf. High. Educ. Adv.* 647–655.
- Taelman, S., Sanjuan-Delmás, D., Tonini, D., Dewulf, J., 2019. An operational framework for sustainability assessment including local to global impacts: focus on waste management systems. *Resour., Conserv. Recycl.* X 2, 100005.
- Taelman, S., Sanjuan-Delmás, D., Tonini, D., Dewulf, J., 2020. An operational framework for sustainability assessment including local to global impacts: focus on waste management systems. *Resour., Conserv. Recycl.* 162, 104964.
- Tandiono, Y., Rau, H., 2022. An enhanced model using the Kano model, QFDE, and TRIZ with a component-based approach for sustainable and innovative product design. *Sustainability* 15 (1), 527. <https://doi.org/10.3390/su15010527>.
- Tantiyaswasdikul, K., 2024. Design thinking for innovation in sustainable built environments: a systematic literature review. *Smart Sustain. Built Environ.* 13 (3), 677–710.
- Tarí, J.J., Sabater, V., 2004. Quality tools and techniques: are they necessary for quality management? *Int. J. Prod. Econ.* 92 (3), 267–280. <https://doi.org/10.1016/j.ijpe.2003.10.018>.
- Turoń, K., 2022. Open innovation business model as an opportunity to enhance the development of sustainable shared mobility industry. *J. Open Innov. Technol. Mark. Complex.* 8, 37. <https://doi.org/10.3390/joitmc8010037>.
- Valentinov, V., 2012. System-environment relations in the theories of open and autopoietic systems: implications for critical systems thinking. *Syst. Pract. Action Res.* 25 (6), 537–542.
- Vignieri, V., 2021. Crowdsourcing as a mode of open innovation: exploring drivers of success of a multisided platform through system dynamics modelling. *Syst. Res. Behav. Sci.* 38 (1), 108–124.
- Vinichenko, M.V., Rybakova, M.V., Chulanova, O.L., Barkov, S.A., Makushkin, S.A., Karacsony, P., 2021. Views on working with information in a semi-digital society: its possibility to develop as open innovation culture. *J. Open Innov. Technol. Mark. Complex.* 7 (2), 160. <https://doi.org/10.3390/joitmc7020160>.
- Vital, X., Krishnan, A., Wyman, H., 2024. Pushing the boundaries of LCA with AI integration and advanced life cycle inventories for semiconductor production, International Conference Electronics Goes Green 2024+: From Silicon to Sustainability, EGG 2024 – Proceedings.
- Wang, Q.R., 2024. Towards zero-emission urban mobility: Leveraging AI and LCA for targeted interventions. *Build. Simul.* 17 (10), 1653–1657.
- Wang, C., Huang, Y., 2024. Philosophy of creative thinking: how philosophical concepts in cultural and creative design inspire innovation and expression. *Cult. Int. J. Philos. Cult. Axiolog.* 21 (2), 259–279.
- Wang, N., Wan, J., Ma, Z., Zhou, Y., Chen, J., 2023. How digital platform capabilities improve sustainable innovation performance of firms: The mediating role of open innovation. *J. Bus. Res.* 167, 114080. <https://doi.org/10.1016/j.jbusres.2023.114080>.
- Williamsson, J., Sandoff, A., 2023. Holding hands on the platform: exploring the influence of municipal open innovation platforms on sustainable business model innovation. *Cities* 140, 104455.
- Wilson, G.A., Case, T., Dobni, C.B., 2023. A global study of innovation-oriented firms: Dimensions, practices, and performance. *Technol. Forecast. Soc. Change* 187, 122257.
- Wnuk, K., & Runeson, P. (2013). Engineering Open Innovation – Towards a Framework for Fostering Open Innovation (pp. 48–59). https://doi.org/10.1007/978-3-642-39336-5_6.
- Wolniak, R., 2018. The use of QFD method advantages and limitation. *Prod. Eng. Arch.* 18 (18), 14–17. <https://doi.org/10.30657/pea.2018.18.02>.
- Wurster, F., Di Gion, P., Goldberg, N., Pfaff, H., Karbach, U., 2024. Roger's diffusion of innovations theory and the adoption of a patient portal's digital anamnesis collection tool: study protocol for the MAiBest project. *Implement. Sci. Commun.* 5 (1), 74.
- Yaghoubi, V., Kumru, B., 2024. Retrosynthetic life cycle assessment: a short perspective on the sustainability of integrating thermoplastics and artificial intelligence into composite systems. *Adv. Sustain. Syst.* 8 (5), 2300543.
- Yamagishi, K., Seki, K., Nishimura, H., 2018. Requirement analysis considering uncertain customer preference for Kansei quality of product. *JAMDSM0034–JAMDSM0034 J. Adv. Mech. Des., Syst., Manuf.* 12 (1). <https://doi.org/10.1299/jamdsm.2018jamdsm0034>.
- Yang, C., Zhang, L., Wei, W., 2022. The influence of introducing the concept of sustainable system design thinking on consumer cognition: a designer's perspective. *Systems* 10 (4), 85. <https://doi.org/10.3390/systems10040085>.
- Yun, J.J., Ahn, H.J., Lee, D.S., Park, K.B., Zhao, X., 2022. Inter-rationality; modeling of bounded rationality in open innovation dynamics. *Technol. Forecast Soc. Change* 184, 122015. <https://doi.org/10.1016/j.techfore.2022.122015>.
- Yun, J.J., Kim, D., Yan, M.-R., 2020. Open innovation engineering—preliminary study on new entrance of technology to market. *Electronics* 9 (5), 791.
- Yun, JinHyoo Joseph, Kim, D., Yan, M.-R., 2020. Open innovation engineering—preliminary study on new entrance of technology to market. *Electronics* 9 (5), 791. <https://doi.org/10.3390/electronics9050791>.
- Yun, J.J., Zhao, X., Jeong, E., Ahn, H., Park, K., 2024. Micro open innovation dynamics under inter-rationality. *Technol. Forecast. Soc. Change* 201, 123263.
- Yun, Jinhyo Joseph, Zhao, X., Ma, L., Xu, Z., Liu, Z., 2023. Open innovation and multi-homing of delivery platforms: comparative study of Cardiff, Daegu and Nanjing. *Eur. Plan. Stud.* 31, 576–597. <https://doi.org/10.1080/09654313.2022.2069463>.
- Yun, J.J., Zhao, X., Ma, L., Liu, Z., Yang, B., 2023. Open innovation dynamics and evolution in the mobile payment industry—comparative analysis among Daegu, Cardiff, and Nanjing. *Eur. Plan. Stud.* 31 (5), 862–884.
- Zhu, Y., Tian, D., Yan, F., 2020. Effectiveness of entropy weight method in decision-making. *Math. Probl. Eng.* 2020, 1–5. <https://doi.org/10.1155/2020/3564835>.