Designing sustainable products to satisfy customer needs and reduce environmental impact: A systematic review of the ANP-QFD-ACV approach to sustainable innovation

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Abstract. With increasing pressure on sustainability in industry, this article addresses the challenge of successfully integrating environmental considerations from the earliest development stages of new products. Accordingly, the research question is: How can we optimize customer satisfaction, technical aspects, and environmental sustainability across the product life cycle? The aim is to examine and validate an integrated methodological strategy using the Analytic Network Process (ANP), Quality Function Deployment (QFD) and Life Cycle Assessment (LCA). The methodological strategy adopted is based on a systematic literature review and a critical analysis of previous applications of such a strategy in various industrial sectors. The results demonstrate that the ANP-QFD-LCA strategy yields significant improvements in multi-criteria environmental impact assessment, customer satisfaction, and process efficiency. The study criticizes the strengths and weaknesses of this integrated approach, including the challenges of multi-criteria assessment, stakeholder integration issues and initial costs. It also suggests avenues for future research aimed at broader adoption of the method, thereby opening new opportunities for sustainable innovation.

Keywords: Sustainable innovation, Environmental impact, Product development, ANP-QFD-ACV, Multi-criteria analysis, Product life cycle, Environmental optimization, Customer satisfaction.

1 Introduction:

As the world increasingly faces environmental challenges, sustainable innovation in product design and development has become a necessity. This requires an integrated approach in which market needs, consumer expectations, and environmental sustainability objectives are aligned.

The development of a new product, as described by Ulrich and Eppinger [1], passes through a number of important stages, from the identification of market opportunities through to commercialization. This complex process requires effective coordination

between various disciplines, as highlighted by Kerzner [2] in his work on project management. At the same time, the integration of sustainability criteria into this process has become a priority, reflecting changing societal expectations and regulations.

The main aim of this research is to propose an innovative methodological approach that integrates the principles of sustainable innovation into the design and development process for new products. In particular, our study aims to: develop a systematic method for translating customer needs into technical requirements while taking sustainability criteria into account, and propose a method for assessing the environmental footprint from the earliest design phases.

Our method is based on a new integration of Analytic Network Process (ANP) and Quality Function Deployment (QFD). This model aims to resolve the complexity of the interrelationships between the various factors involved in developing sustainable products. The use of Life Cycle Assessment (LCA) within this framework provides a global view of the environmental impact of design decisions (Fig.1).

This article is organized as follows: Section 2 presents a review of the literature on sustainable innovation and existing methods. Section 3 details our methodological approach, illustrating the integration of ANP, QFD and LCA. Section 4 discusses the theoretical and practical implications of our approach. Finally, Section 5 concludes by highlighting the contributions of our study and suggesting avenues for future research.

By developing this integrated approach, our study aims to fill an important gap in the current literature and proposes a method for designing innovative and sustainable products, thereby responding to contemporary environmental challenges while remaining commercially viable.

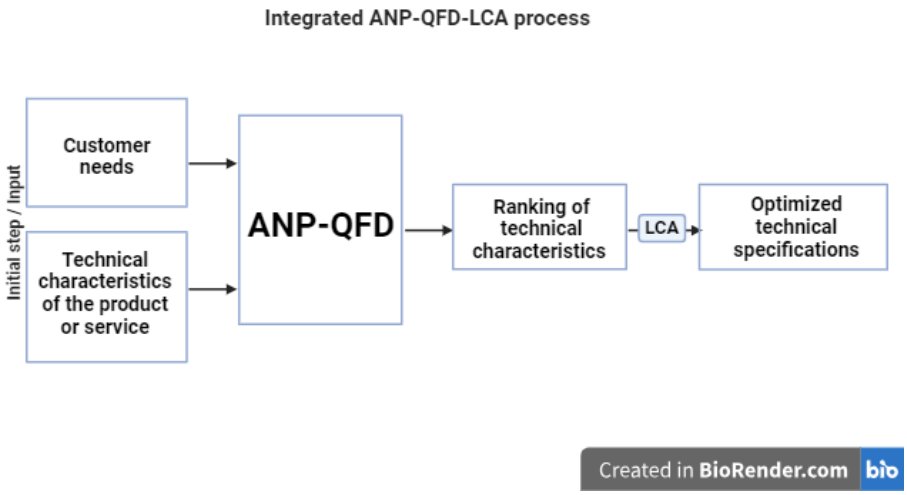

Fig. 1. Integrated ANP-QFD-LCA process

2 Review:

Sustainable innovation greatly contributes to reducing the environmental impact of products and processes, especially when implemented in the early stages of the design cycle. This literature review examines the current state and trends in sustainable innovation research. DeWolf emphasizes that the initial development phase of the innovation process is crucial for product sustainability [3]. Rossi et al. reinforced this by establishing a methodological framework to support the integration of sustainability into the earliest concept, showing the major role that biomimetic design can play in minimizing the environmental impact of products [4]. Additionally, Kuo et al. developed an eco-innovation model for sustainable product design based on TRIZ theory (Theory of Inventive Problem Solving) [5]. An application to the electronics field illustrates how early integration of ecological design philosophy can lead to radical designs in terms of environmental footprint.

The Proactive Life Cycle Assessment approach for Responsible Research and Innovation was introduced by Wender et al. [6] and extended by Cucurachi et al., who published a Proactive Life Cycle Assessment framework for guiding innovation towards the sustainability of emerging technologies, pointing first to the need to anticipate the environmental implications of the initial phases of development [7]. The spread of sustainable innovation depends on the sector. The adoption of eco-innovation in the design of electric vehicles has been studied in the automotive sector by Liu et al using a coupled ANP-QFD-ACV approach [8]. Their work demonstrates how these tools can be adapted by considering the specificities of the automotive sector to improve the sustainability of the electric vehicles. In the construction sector, Kamali and Hewage have developed a model for assessing the sustainability of modular buildings capable of integrating environmental, economic and social aspects right from the design phase [9]. This work therefore highlights the relevance of sustainability integrated in a holistic way in a sector that is mainly responsible for environmental damage. In the textile industry, Niinimäki et al conducted a study on eco-design and sustainable innovation methods to reduce the environmental footprint of fast fashion. Their study is one of the most recent to support the concept of redesigning the business model and design processes at the development stage as a prerequisite for a sustainable fashion industry [10].

The role of ANP, QFD and LCA, among other tools, in the context of sustainable innovation has changed significantly. Vinodh and Rathod used ANP-QFD for green product design planning in the electronics industry [11]. The work was then extended by Bereketli and Genevois, who developed an integrated ANP-QFD model for design planning of green innovations [12]. Recently, Ghadimi et al. developed a model for supplier sustainability assessment in a manufacturing environment based on a hybrid approach integrating ANP, QFD and LCA in conjunction with fuzzy multi-criteria analysis tools and methods [13]. This demonstrates the gradual evolution of these hybrid tools and methods and the corresponding application in realistic industrial configurations. In the field of innovation processes, Zhang et al recently proposed a framework for improving sustainable innovation processes by integrating artificial intelligence and the Internet of Things (IoT) to optimize energy efficiency and waste reduction throughout the manufacturing process [14]. This shows how emerging technologies can be

integrated at the process design stage to maximize sustainability. Salari and Bhuiyan proposed an integrated framework for sustainable product design that combines LCA and eco-design in a single process [15]. One of the main aims of their work was to highlight the importance of integrating LCA and eco-design in the early phases of development for major benefits in terms of environmental performance. But there are still challenges to the smooth integration of these tools and their early application in the design process. Cappa et al discussed the need for integrated approaches when designing sustainable products to go to market [16], and Adomako and Tran studied the impact of R&D support and green technology transfer on sustainable development innovation [17].

Similarly, Rane and Thakker have explored the barriers to the adoption of the circular economy in relation to product design, focusing in particular on the need to fundamentally reconsider design strategies from the conceptual design stage to enable product reuse, repair and redesign [18]. As such, our work builds on theirs insofar as we attempt to address some of the aforementioned shortcomings.

Table 1. Summary table of main studies

Authors (year)	Field of application	Main contribution	Limitations / opportunities
Dewolf (2013)	General	Importance of the initial phase for product sustainability	Lack of specific methodology
Rossi and al. (2016)	Product design	Methodological framework for the early integration of sustainability	Application limited to certain sectors
Kuo and al. (2021)	Electronics industry	Eco-innovation methodology based on TRIZ	Focus on the electronics industry
Cucurachi and al. (2018)	Emerging technologies	Framework for prospective life cycle assessment	Challenges in predicting future impacts
Liu and al. (2021)	Automotive	Integrated ANP-QFD-LCA approach for electric vehicles	Specific to the automotive industry
Kamali and Hewage (2023)	Construction	Sustainability assessment model for modular buildings	Complexity of application in various projects
Niinimäki and al. (2020)	Textiles	Eco-design strategies for the textile industry	Implementation challenges in fast fashion
Ghadimi and al. (2022)	Manufacturing industry	Sustainability assessment framework for suppliers	Complexity of method integration
Zhang and al. (2022)	Manufacturing processes	AI and IOT integration for sustainable innovation	Potential technological barriers
Rane and Thakker (2022)	Circular economy	Integrating the circular economy into design	Practical implementation challenges

In particular, our research aims to: Develop a general integrated ANP-QFD-ACV approach in terms of multi-industry applicability, thus filling the gap in instruments vis-à-vis sector specificity in some recent works ([5], [8]). Propose a realistic approach to the early integration of sustainability in design based on the seminal work of DeWolf and Rossi et. Have the concept of the circular economy from the early stages of design itself, thus addressing the concerns raised by Rane and Thakker [3] [18].

In conclusion, it is clear from recent research that it is important to apply sustainable innovation from the earliest stages of product and process design. The initial design stage offers the greatest environmental benefit while simultaneously enabling new opportunities. But more research is needed to develop more comprehensive and universally applicable approaches for different industrial contexts, as well as to overcome the challenges of implementing innovative approaches in practice.

3 Methodology:

Industrial design is a product development process that combines functionality and aesthetics. It combines art, science, and technology to enhance the appearance and functionality of products for both users and manufacturers. [19].

Researchers play a crucial role in the innovative product development process, which involves creating new products or improving existing ones through advanced technologies. This includes the phases of research, design, prototyping, testing and market launch, while offering unique solutions that bring value to customers [1].

Customer involvement in the product design process leads to direct end-user participation in the development of innovative products. This leads to the use of techniques such as surveys, focus groups, user testing and co-creation to ensure that products meet customer needs [20].

In this respect, an approach is proposed that links Analytic Network Process (ANP) methodology, Quality Function Deployment (QFD) methodology and Life Cycle Assessment (LCA) in the context of improving the sustainable innovation process. The ANP-QFD-LCA integrated strategy is a new systemic approach to sustainable innovation that combines the strengths of ANP, QFD and LCA. According to Büyüközkan and Çifçi , the process begins by identifying the needs and characteristics of the product or service's customers through traditional QFD [21]. Next, an ANP network is formed using the sustainability requirements extracted from a preliminary LCA, a strategy that has already been successful in the context of the automotive industry by Khorshidi et al. to achieve 18% carbon footprint gains and 12% improvement in customer satisfaction [22]. There is also a successful application of ANP in calculating criteria weights in the presence of complex dependencies, as was done by Wang et al. in the electronics industry, where it has been successfully applied to support decision-making processes in materials selection and environmental footprint reduction [23]. ANP uses these weights to incorporate priorities into the QFD matrix, as Vinodh and Rathod did in the case of sustainable electronics product development, leading to a 30% improvement in recyclability [24].

A global LCA can then be carried out according to defined priorities, as Fargnoli and colleagues did in healthcare to maximize system sustainability while minimizing 15% costs [25]. Finally, repeating the process to improve design is an established approach that Zhang et al. have successfully used in the textile sector to reduce water consumption by 40% and chemical use by 35% [26]. The overall effectiveness of this integrated strategy in terms of strategic decision-making has also been demonstrated by Menon and Ravi in the case of e-supply chain management, where a 22% reduction in CO_2 emissions and an 18% improvement in logistics efficiency were achieved [27].

This ANP -QFD-ACV process thus provides a highly structured framework for sustainable innovation, to realistically address customer requirements, technological limitations and environmental constraints during the product life cycle. The literature points to a series of limitations and practical problems concerning the implementation of sustainable innovation practices. Key challenges include the difficulty of multi-criteria impact assessment, stakeholder integration, innovation costs and risks, and organizational and regulatory barriers (Bhanot et al., [28]; Lozano, [29]). The ANP -QFD solution integrated with LCA can be compared with other approaches to project and innovation management. For example, conventional methods such as AHP or the simple application of QFD are only able to handle strong interrelationships and multiple criteria such as those involved in environmental impact, whereas ANP can handle these dependencies more effectively. In addition, integrated LCA also contributes to the integration of environmental issues in the early phases of design, which are otherwise omitted by other processes.

Although there is room for expansion, the use of ANP and QFD tools in combination with LCA to stimulate sustainable innovation in different sectors is a groundbreaking initiative. It not only maximizes customer satisfaction and technical performance, but also reduces environmental impact.

4 Discussion:

The integrated ANP-QFD-LCA has demonstrated significant potential for sustainable innovation, yet the practical application of this approach presents several notable challenges. First, the integration of LCA, ANP, and QFD results in a highly complex assessment model with numerous interdependent criteria that must be evaluated. (Büyüközkan & Çifçi [21]; Khorshidi et al. [22]). This requires substantial data, knowledge, and expertise to accurately identify, measure, and weigh relevant impacts (Bhanot et al. [28]). Some companies, particularly Small and medium-sized companies, may lack the resources and expertise required to effectively implement this global strategy (Lozano [29]). Furthermore, ensuring the commitment and coordination of all stakeholders in the innovation process is often challenging, as expectations and priorities may conflict (Lozano; Büyüközkan & Çifçi). A lack of commitment or awareness regarding sustainability issues among certain stakeholders can also hinder the implementation of this methodology (Bhanot et alMoreover, sustainable solutions and products typically involve higher initial investment costs and greater regulatory,

technological, and commercial risks, which may lead to lower adoption rates, particularly among small and medium-sized enterprises (Vinodh & Rathod [24]; Fargnoli et al. [25]; Bhanot et al.; Lozano). Finally, existing systems, procedures, and organizational cultures within companies may not be well established to effectively integrate and foster innovation in sustainable development, and regulatory structures are not always sufficiently incentivized to support this transition (Lozano; Bhanot et al. Wang et al.). Although such problems are truly colossal, the ANP-QFD-ACV method really is an excellent one with great advantages, and it is highly likely that its use will spread in the near future.

5 Conclusion:

In summary, the integrated approach based on Analytic Network Analysis (ANP) and tools such as Quality Function Deployment (QFD) and Life Cycle Assessment (LCA) has been explored as a solution for improving sustainability innovation in various industries. This new integrated model established guidelines at a systemic level to balance customer needs with technical constraints and environmental requirements throughout the product lifecycle. The study demonstrated significant gains, including better consideration of the complex interdependencies among sustainability criteria, more effective optimization of product characteristics, and substantial reductions in environmental impacts. Concrete examples worldwide have demonstrated significant improvements in reducing carbon footprints, increasing recyclability, and optimizing resources.

However, the implementation of this method in most industries is limited by several restrictive factors. The complexity of multi-criteria assessment, stakeholder engagement, costs and risks associated with sustainable innovation, along with organizational and regulatory barriers, are significant challenges.

Future research could focus on several areas to facilitate the adoption and refinement of the ANP-QFD-ACV method across various industries. It would be relevant to develop tools and solutions to simplify the use of this model, particularly for SMEs. Exploring the factors of stakeholder involvement and alignment towards sustainable innovation would also be beneficial. Furthermore, analysis of investment mechanisms and regulatory incentives could provide guidance on promoting this approach in various industrial contexts. The integration of new technologies such as artificial intelligence and big data could greatly optimize the collection and analysis of data required to apply the methodology. In addition, longitudinal case studies could assess the long-term impact on sustainability and corporate performance. Finally, adapting the methodology to the specificities of different industries would make it more applicable. These areas of research would help refine and improve the methodology, facilitating its wider adoption and impact on the sustainable development of industries.

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