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Circular economy in the power electronics industry: innovative design strategies for sustainable life cycle management.

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Abstract

Power electronics (PE) plays a crucial role in the expansion of renewable energy as improving the efficiency and productivity of this equipment is a key factor in increasing the viability, sustainability and competitiveness of renewable energy parks. Despite the attention paid to the development of renewable energy technologies, where PE plays a key role in their performance, there is a notable gap in research on the evaluation of PE and the infrastructure required for its deployment and management. Although there are numerous studies analysing the circular economy (CE) and life cycle analysis (CE-LCA) of renewable technologies, very few focus on assessing the circularity of PE, despite being a significant source of resource consumption, including critical raw materials, and high environmental impact. This study addresses this gap by investigating the application of circular design strategies to improve the sustainability of PE by reducing, slowing down, closing and regenerating resource loops. The methodology includes the classification of European Union eco-design criteria according to CE strategies and the assessment of their applicability in practice based on feedback from industry stakeholders. Based on the results, a critical evaluation of the implementation of different CE strategies in the PE sector is provided. These results highlight the urgent need to integrate closing and regeneration strategies in the design and development of PE to support the circularity and sustainability of the sector, minimising waste and the use of non-renewable materials. Furthermore, the regenerative circular strategy is the least addressed, underscoring the importance of expanding research in this area and developing new renewable materials that offer the same efficiency and performance as conventional materials.

Keywords: circular economy; eco-design; end of life; power electronics.

1. Introduction

The current and future deployment of renewable technologies is essential to support the transition to sustainable energy in order to achieve the European Union's (EU) climate goal of carbon neutrality by 2050 [1]. Renewable energies, such as wind, solar and geothermal, have emerged as key solutions to reduce greenhouse gas emissions and reduce dependence on fossil fuels. In particular, it is expected that by 2030 at least 42.5% of gross final energy consumption will come from renewable sources [2].

As energy demand grows, the expansion of renewable energy technologies could bring significant environmental benefits, such as reduced fossil-fuel use and related air pollution. However, the deployment of renewable energy technologies and infrastructure rely heavily on the implementation of PE devices for an efficient management of the energy flows. Although these technologies promise a cleaner energy system, the conventional design of these PE devices still faces environmental challenges due to their reliance on critical materials such as gallium (Ga), and rare earths such as neodymium (Nd) [3]. Likewise, PE devises are high energy intensive; it is estimated that around 20% of the world's electricity consumption is related to power conversion systems [4]. In this context, the implementation of eco-design and CE strategies have emerged as instrumental mechanisms to reduce the environmental impact of products throughout their life cycle. In particular, the eco-design of PE equipment is essential to improve its environmental sustainability; by integrating environmental considerations from the initial design

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phases, environmental impact can be reduced throughout the entire product life cycle, from the extraction of raw materials to their final disposal.

Focusing on the scientific literature on CE in PE, relevant studies on eco-design and circularity of PE have been identified. The study [5] provides a literature review of the implementation of eco-design in PE. However, it only focuses on four eco-design approaches and is limited to academic research, without verifying with stakeholders the real applicability of these approaches. On the other hand, [6] compiles all international regulations and standards that affect the sustainability of PE. Nevertheless, it does not address how companies can operationalise these practices in their designs. Furthermore, [7] highlights the need to design more circular products to achieve SDG 12, however, it only focuses on modularity to facilitate disassembly and implement end-of-life practices. [8] sets out an approach to establishing a green supply chain in the semiconductor industry, however, it does not offer eco-design aspects related to other life stages of products. [9] analyses the impacts of PEs on global warming but does not analyse how eco-design aspects condition the full circularity and sustainability of PEs. [10] provides a state of the art on the sustainability of PE but does not provide eco-design aspects that can be incorporated into new developments. Much other research focuses on the efficiency and reliability of equipment, in particular, [5] demonstrates that the search of the words ‘efficiency’, ‘power density’, and ‘power electronics’ yielded 2,465 publications globally over the past year (2021-2022) in IEEE.

However, despite these advances, there are still gaps in the practical application of CE strategies in PE. Currently, current literature focuses mainly on theoretical aspects and the development of general guidelines, or on innovations that deepen the efficiency of equipment. But there are few case studies showing eco-design guidelines that help PE to improve the circularity and environmental sustainability of the sector, as well as analysing the actual application of these criteria in the industry. This lack of practical studies makes it difficult to understand the real challenges and benefits of adopting CE practices in the sector.

In this context, our study makes a novel contribution by analysing eco-design criteria derived from the European Ecodesign for Sustainable Products Regulation (ESPR) [11], and classifying them according to CE strategies (Narrow, Slow, Close and Regenerate). We then evaluated these criteria with the PEs industry to identify which of these strategies are being implemented in practice. This approach allows us not only to understand how eco-design criteria align with CE strategies, but also to identify gaps and opportunities for improvement in the application of these strategies in the design and production of PE equipment. Thus, our work offers a practical analysis that complements existing theoretical approaches, providing a clear view of the connection between regulations, CE strategies and industrial practices.

In summary, while literature has advanced the identification of eco-design approaches and the importance of regulation for sustainability in PE, our study distinguishes itself by providing a practical assessment of the applicability of eco-design criteria in the PE industry and by analysing the effective implementation of CE strategies in this sector. In this way, our research not only extends existing theoretical knowledge, but also provides practical guidelines for the adoption of sustainable practices in the PE industry.

2. Methodology

The research followed a four-step methodology (Fig. 1). First, the proposed European Ecodesign for Sustainable Products Regulation (ESPR) [11] was reviewed to create a list of eco-design criteria. Next, these criteria were classified according to the CE strategies to which they belonged, and this list of eco-design criteria was discussed with different industry stakeholders. Next, interviews were conducted with relevant industry stakeholders to analyse the degree of application of CE strategies through the ESPR [11] in the PE industry. Finally, a critical analysis of the results is presented and hot spots and opportunities for improvement are discussed.

2.1. *ESPR review*

The eco-design criteria list was created using as a reference the regulation proposed by the European Union in March 2022. The ESPR [11] was used as a benchmark for this study mostly because it is the regulation set up by the EU to address eco-design requirements and the environmental sustainability of products. This directive covers essential aspects of sustainability that are key for PE and is completely aligned with other European standards and regulations, such as ISO 14001 [12].

After reviewing the proposal carefully, all eco-design criteria were extracted to create a list of eco-design criteria for further evaluation by industry stakeholders. As a result, a list of 36 criteria to be considered in the design of products was established (Table 1).

2.2. Classification according to CE strategies

The second methodological step comprised the classification of the eco-design criteria according to the four major CE strategies [18]:

- Narrowing: Use less raw materials, encompassing components, materials and energy during the design, production, delivery, use, and recovery.
- Slowing: Use products, components and materials longer. Extend the product life.

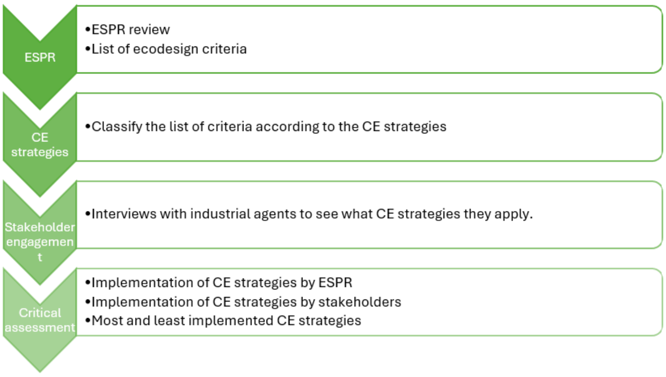

Fig. 1. Methodological steps

- Closing: Use again Incorporating post-consumer waste back into the economic cycle.
- Regenerate: Management of natural ecosystems, use of renewable and non-toxic materials and renewable energy.

2.3. Stakeholder engagement

Stakeholder engagement was carried out as a key step to test the application of eco-design strategies in the PE industry. To this end, 90-minute interviews, both online and in person, were conducted with different stakeholders to discuss the applicability of the selected eco-design criteria in terms of relevance and feasibility, following the approach of Ruíz de Azua-Lahidalga et. al [13] and Picatoste et al [14]. Each criterion was evaluated in terms of relevance and technical feasibility, and stakeholders assigned scores to determine priority levels. The scales used for the assessment were: importance - 0 not at all important, 1 not very important, 3 moderately important, 9 very important; and feasibility - 0 totally unfeasible, 1 probably unfeasible, 2 not very feasible, 3 moderately feasible, 4 quite feasible, 5 absolutely feasible. The multiplication of both variables determines the priority level of each criterion.

Three interviews were conducted with experts from different institutions involved in the design and development of PE, covering different technology readiness levels (TRL). For confidentiality reasons, the names of the organizations and experts interviewed cannot be provided, so during the article we will refer to them as follows:

- High Education Institution: Researcher in PE systems applied to electric power control (HEI).
- Technological Center: Expert working on the design and control of PE (TC).
- Multinational Company: Multinational company that manufactures and markets PE converters (MC).

2.4. Critical assessment of the application of CE strategies

Finally, a critical analysis of the application of CE strategies in the PE industry using eco-design criteria in their development was addressed. On the one hand, the results related to the CE strategies associated with the ESPR [11] eco-design criteria are described. On the other hand, the CE strategies applied in the industry are discussed, focusing on the most and least applied aspects by the PE industry. In addition, improvement guidelines for the industry are proposed.

3. Results and discussion

3.1. ESPR eco-design criteria classified by CE strategies

After analysing the European ESPR proposal [11] in depth, a list of 36 eco-design criteria classified by the four CE strategies (narrow, slow, close and regenerate) has been defined (table 1.)

Table 1. ESPR eco-design criteria classify by CE strategies

Eco-design criteria	CE strategy
Reduce the weight and size of the materials, components and products	Narrow
Reduce production wastes	Narrow
Reduce the number of processes and components	Narrow
Increase the efficient use of energy and resources	Narrow
Substitute and/or reduce the use of hazardous substances (comply EN62474)	Narrow
Avoid and/or reduce and ensure the right management of critical raw materials (CRM) and non-regulated CRM (comply EN62474)	Narrow
Comply with CE marking and declaration of conformity	Narrow
Ensure the use of digital product passport (DPP)	Narrow
Reduce energy consumption and emissions from transportation and logistics	Narrow
Optimise shape and volume for maximum packaging density, reducing the (over) packaging and waste	Narrow
Maximise material and energy efficiency during use	Narrow
Ensure modularity	Slow
Ensure easy components assembly	Slow
Ensure reliability and durability	Slow
Extend product lifetime	Slow
Facilitate the inspection and accessibility of joints and components, easy to remove	Slow
Maximise the availability and delivery of spare parts	Slow
Provide extended warranty periods and facilitate support services	Slow
Include updates/upgrades software and hardware of the product to newer versions	Slow
Maximise repairability rate	Slow
Ensure easy and non-destructive disassembly	Slow
Minimise disassembly steps and time	Slow
Identify and facilitate the extraction of substances, mixtures, and components	Slow
Maximise remanufacturability rate	Slow
Maximise reusability rate	Slow
Set up effective collection systems	Slow
Select and/or increase use of reused, recovered and recycled materials	Close
Reduce the use of different types of materials	Close
Avoid technical solutions detrimental to reuse and recycling of components and whole appliances	Close
Maximise product recyclability rate	Close
Maximise materials recoverability rate	Close
Increase the quantity, quality and efficiency of remanufacturing, recycling and recoverability processes	Close
Identify and facilitate the extraction of substances, mixtures, and components	Close
Ensure material flows for circularity	Close
Minimise the amount of non-recoverable waste	Close
Select and/or increase use of renewable resources	Regenerate
Reduce emissions to air, water and soil and anticipated pollution	Regenerate

Looking at the overall allocation of the criteria according to the different CE strategies, there is an uneven distribution among the four CE strategies. About 28% of the criteria fall under the narrowing strategy, which seeks to reduce resource consumption. The largest proportion, 42%, corresponds to the slowing strategy, which focuses on extending the useful life of products. Thirdly, 25% of the criteria are associated with the closing strategy, which promotes the reintegration of waste generated in the CE cycle. Finally, the remaining 5% are assigned to the regenerate strategy, which is oriented towards the management of natural systems.

This may be due to several reasons, firstly, the slowing strategy focuses on extending the life cycle of products, which is one of the key aspects of the CE, and is present in various European policies such as UNE EN 45552 [15], which sets requirements to improve durability or the 2019/2021 regulation that sets requirements on repairability, in order to extend the life of products [16]. By designing more durable products, the use of new resources and the generation of waste are minimised, which minimises the environmental impact of products [17]. In turn, making efficient use of resources (narrow strategy) is also key to moving towards a sustainable economy, so there are different regulations that affect the energy performance of products [18]. Both the reduction in the use of materials and energy efficiency are pillars of eco-design.

On the other hand, although closure and regeneration strategies are fundamental to achieving full circularity, they are given less importance in the regulations, mainly due to the technological and economic challenges they present. The reason why the other two CE strategies are given more emphasis is clear, but the reason why these strategies are not given as much importance is less so. Firstly, it may be due to the technical difficulties of recycling and recovery infrastructures or to the difficulty of separating materials [19]. Secondly, there are studies that confirm that narrow and slow strategies allow a greater increase in resource efficiency than simply closing resource flows through recycling [20]. In addition, there is no demand for these types of materials, which limits the manufacturers' commitment to these technologies [13].

It should be noted that this European proposal focuses mainly on industrial products, where it is more difficult to apply criteria that help to restore and improve the natural ecosystem. Principles such as the use of renewable materials are easier to apply in agriculture [21]. At present, industrial sectors can hardly help in the regeneration of ecosystems.

In conclusion, close and regenerate strategies require transformations in economic models and infrastructure to integrate recovery, recycling or regenerative processes that go beyond eco-design directives. Whereas the aspects of durability (slow) or resource efficiency (narrow) are easier to implement.

3.2. Application of CE strategies in the PE industry

In addition to analysing the importance of each strategy for the European ESPR proposal [11], the implementation of these strategies with the PE industry has been analysed and the different synergies and trade-offs between these results and the ESPR vision have been studied, where it should be noted that both visions largely coincide.

3.2.1. Narrowing resource loops

The most widely implemented strategy in the industry is narrowing, where 83% of the eco-design criteria are. This is due to the fact that the efficient use of energy and material resources is a priority for them for different reasons; economic, legislative and technological. Specifically, the MC's experts emphasize that "*we try to optimise the designs to the maximum so that there is no waste, in the end it is money wasted. We have measurement programs to control the efficient use of resources".*

PE is the technology associated with the efficient conversion, control and conditioning of electrical energy, so it is key to maximise energy efficiency, minimising energy consumption and environmental impact. In addition, there are regulations that oblige energy-related products manufacturers to optimise their equipment to reduce the energy consumption of their equipment. Or RoHS Directives [22], which limit the use of hazardous substances in electronic products.

On the other hand, PE technology research is focused on the introduction of new semiconductor materials that are more efficient, such as silicon carbide (SiC) or gallium (Ga), allowing the industry to reduce the energy consumption of their equipment thanks to their material properties [23]. In addition to making the equipment more energy efficient, they are smaller and lighter in size and weight, which benefits them in both economic and environmental terms [24].

The lowest-rated criterion is *Comply with CE marking and declaration of conformity.* However, it should be noted that while the HEI and TC do not apply it, the manufacturer does. This is mainly due to the nature of the organizations and the activities they carry out. The university and technology center are mainly focused on research and development of new concepts, which are generally not commercialized in the market, so they are not obliged to comply with CE marking. However, the manufacturer is obliged to ensure that its products comply with the CE marking before marketing any product.

3.2.2. Slowing resource loops

Together with narrowing, the most applied strategy is slowing, where it is applied by 71%. This is mainly because the durability and reliability of products is key for consumers of PE equipment. According to the TC expert, customers are looking for "*less replacement or maintenance*" of equipment as they "*save on maintenance and repairability costs*."

PE are an essential part of critical applications such as electric vehicles or renewable energy parks, where technical failures can lead to major losses, both financial and reputational.

On the other hand, this strategy enhances the modularity and repairability of the equipment. PE equipment is designed to be as modular as possible, to minimise downtime as much as possible and not to discard all the equipment when a component fails [25]. According to the university expert, "*we try to make modular designs to make it easier to fix. If something burns out, they can just replace the component. You change what goes wrong and the application continues to* *work*". In addition to this, there are initiatives in Europe that promote the right to repair, reinforcing the slow strategy [16].

On the other hand, the criteria of *maximising the reuse rate* and *ensuring the use of the digital product passport (DPP)* are the least applied in the industry. On the one hand, the DPP is still in the development phase in Europe, due to confidentiality issues there are still doubts as to how this can be materialized in the European industry, so as it is not a mandatory requirement it is not yet applied, although it is true that the university expert claims to know of its existence. On the other hand, they do not use reused elements, mainly because as they do not know the exact state of the equipment, they cannot risk using them and that they do not comply with safety and reliability standards. The useful life of PE equipment is relatively long, where the elements suffer considerable wear and therefore their reuse is not viable. In addition, in many cases the equipment is specifically designed for specific applications, so it cannot be reused in other applications.

3.2.3. Closing resource loops

In contrast, the application of the close and regenerate strategies is practically nil, with only one criterion out of eight (11%) applied in the case of the close strategy and none in the case of the regenerate strategy. The application of criteria related to the closing of the material cycle is difficult due to the great complexity of the design of this equipment. As mentioned, the trend in PE is moving towards miniaturization of devices, complicating disassembly and separation of materials. In addition, these products contain a wide variety of materials, including hazardous materials such as brominated flame retardants, which further complicates the recovery and recycling process [3]. Also, as the TC expert confirms, there is a lack of a secondary market for these types of materials "*we have never considered using reused elements, we buy them new. But we don't know anyone in the industry who is implementing them, so rather than technical difficulties in incorporating these elements, we see supply and demand difficulties".*

Instead, the only criterion they apply from the close strategy in PE is to *reduce the use of different types of materials.* The reason for this is that homogenizing materials simplifies manufacturing and logistics processes, which leads to cost reduction.

3.2.4. Regenerate resource loops

Finally, none of the three industrial players involved in the study use renewable materials in their designs or minimise the amount of non-recoverable waste, so the CE Regenerate strategy is not applicable to the PE industry. This is mainly due to the high efficiency and performance required of this equipment. Control circuits and semiconductors require specific properties such as high thermal resistance, which in many cases biomaterials do not provide effectively. Replacing conventional materials with biomaterials could compromise the functionality and lifetime of the products, which goes against the goals of PE: reliability and energy efficiency (aligned with the narrowing and slowing strategies). In the words of the TC expert, "*we know of no renewable materials that can achieve the efficiency levels required for our applications*."

On the other hand, the technical complexity of the products and the lack of effective recycling technologies to separate advanced materials make it difficult to minimise non-recoverable waste, which reduces the applicability of the regenerate strategy.

4. Conclusions

This article presents a list of 36 eco-design criteria extracted from the European ESPR proposal [11] that have been categorized according to the CE strategies: narrowing, slowing, closing and regenerating. From this classification we conclude the importance of each of the CE strategies for the ESPR [11], where the narrowing and slowing strategies are prioritised over the closing and regenerate strategies. This is mainly due to the fact that this proposal is oriented towards industrial products, where priority is given to the extension of the useful life in order to reduce waste and the efficient use of resources, in order to reduce the demand for new critical materials, among others.

After conducting the study with three different stakeholders, we observed an alignment between the priorities of the PE industry and the objectives set out in the ESPR [11]. The PE industry focuses on ensuring the durability and reliability of its equipment while designing it to be easily repairable. In this sector where longevity and reliability are key, the slowing strategy is critical to meet regulatory pressures and market needs.

Another essential factor in PE is energy efficiency, where improving the efficiency of frequency converters in industrial applications could reduce global CO_2 emissions by approximately 1.5 gigatons per year by 2030 [4]. Therefore, implementing the criteria of the narrowing strategy is essential to achieve better sustainability of this equipment.

On the other hand, closing and regenerating strategies are particularly challenging for the PEs industry due to a combination of material limitations, technology constraints and systemic factors. PE relies heavily on materials such as silicon, rare earth metals (e.g. neodymium) and other valuable metals (e.g. copper). These materials are critical to their high performance requirements, but are not easily substitutable with renewable or recycled counterparts. On the other hand, many PEs materials degrade during use, making them unsuitable for direct reuse or high-quality recycling. On top of this, PEs are often highly integrated, with multiple layers and compacted components, making disassembly and material recovery difficult. Another constraint to effectively implement close and regenerate strategies is the cost of recovering end-of-life PEs materials and the lack of infrastructure.

In addition, there is a lack of industrial incentives for renewable materials. Renewable or biodegradable materials are not yet standardised for PEs, and their adoption would require significant changes in supply chains and product design, making the industry resilient to change. Encouraging this could change the trend in the sector and make them more open to new solutions.

However, in recent years there have been major advances in the development of new semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), which help the sustainability of the industry through their ability to improve energy efficiency, thermal performance and miniaturisation of

PEs. These benefits reduce equipment energy consumption and greenhouse gas emissions during the use of PEs. However, these semiconductor materials also have challenges to address in order to improve their sustainability. On the one hand, the extraction and production of SiC and GaN involve high energy and resource demands. For example, the specific energy consumption of traditional furnace installations ranges between 25.2 and 28.8 GJ per tonne of SiC at 100 % produced [26]. Secondly, the manufacture of advanced semiconductors involves the use of hazardous chemicals and generates toxic by-products. For example, GaN production uses toxic products such as ammonia that require careful management to avoid environmental damage [27]. Despite these challenges, SiC and GaN are the materials of the future due to improved energy efficiency in key applications for the sustainability of the planet such as renewable technologies or electric vehicles. Overcoming the environmental challenges posed by these materials is therefore essential to ensure their viability compared to current alternatives.

In summary, the PE industry shows a clear alignment with the ESPR priorities [11], especially in the Slow and Narrow strategies, which focus on durability and energy efficiency. However, the limited implementation of Close and Regenerate suggests that, to achieve greater circularity and sustainability of equipment, it would be advisable for government institutions to promote the creation of supply chains that prioritise the use of recycled materials in the manufacture of new equipment, reducing reliance on virgin raw materials. Including eco-design criteria identified in the ESPR can improve the circularity and sustainability of PE. For example, manufacturers should prioritise modular and reparable designs to extend the lifespan of PE. Ensuring the availability of spare parts and standardising components across models would facilitate maintenance and repairs, reducing waste generation. Also, early-stage design decisions should focus on using recyclable and sustainable materials. Incorporating guidelines for material efficiency, such as minimising non-recoverable waste, can significantly improve end-of-life management. In addition, standardising disassembly protocols would facilitate the recovery and recycling of valuable materials and components, such as metals, control circuits and semiconductors. Furthermore, research into more sustainable materials and new semiconductor materials, such as SiC and GaN, which do not compromise the technical performance of products, should be encouraged to offer viable and environmentally sustainable alternatives. Not forgetting that the use of renewable sources in the production of this equipment would contribute to minimising its carbon footprint, helping the regeneration of ecosystems.

5. Limitations and future lines of research

The limitations of this study, and therefore potential future research directions, lie mainly in the limited number of interviews and in being a qualitative study only. On the one hand, the limited number of stakeholders involved in this study could restrict the representativeness of the results for the sector, which is recognised as a limitation and an important direction for future research. Nevertheless, the three stakeholders cover key stages of the life cycle of PEs products, allowing for a preliminary understanding of the overall needs and challenges of the industry from different perspectives (e.g. TRL levels). However, extending the study to other stakeholders, such as distributors, waste managers and policy makers, would significantly enrich the results. These perspectives would provide a more holistic understanding of industry dynamics and better inform implementation strategies of the CE principles.

On the other hand, the qualitative criteria assessed in this research broadly represent the PE industry's perception of the application of eco-design strategies. Qualitative assessments are essential to preliminarily identify the most relevant aspects of circularity and sustainability, providing practical information to guide more specific quantitative studies. These assessments are particularly useful in the early stages of projects, when limited information is available. This approach not only optimises the use of resources and time, critical aspects in the development of life cycle assessments (LCAs), but also ensures that subsequent quantitative metrics focus on the areas with the greatest potential impact, maximising their relevance and effectiveness. Therefore, complementing qualitative results with the integration of LCA and quantitative tools is one of the future directions of this work, which will help to measure the environmental impacts associated with applied circular design strategies.

Furthermore, another future direction of this research may be to extend it to non-EU contexts, such as Asia, North America or emerging economies. Differences in political priorities, market demands, and cultural attitudes may significantly influence the adoption and implementation of eco-design practices in other regions. Therefore, this future line of research could be very enriching and could highlight both commonalities and regional adaptations**.**

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