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Design measures to address carbon emissions in products' lifecycle: an empirical analysis

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Abstract

Companies need to implement low-carbon operations, including product-related innovation initiatives. The literature on low-carbon product design has grown, but existing studies are primarily theoretical. This empirical study identifies design measures adopted by companies committed to GHG emission reduction. A qualitative analysis of the climate change reports from a sample of companies reporting to the CDP was conducted. Design measures were identified and classified. The findings shed light on design measures contributing to emission reduction in different product lifecycle phases.

Keywords: low-carbon design, sustainability, sustainable design, product lifecycle management (PLM)

1. Introduction

Companies play a significant role in global greenhouse gas emissions (GHG), and their commitments to decarbonisation are pivotal in the fight against climate change (Krabbe et al., 2015; Wade and Rekker, 2020). In light of the imperative to reduce global temperature rise by decarbonising industrial activities, organisations across sectors have set targets for reducing GHG emissions, including science-based targets. These science-based targets provide organisations with a roadmap for reducing GHG emissions in line with the latest climate science, aligning with the goals of the Paris Agreement. By defining these targets, companies can ensure that their direct and value chain emissions align with the scientifically defined limits and do not contribute to climate impact. In tandem with these ambitious targets, organisations must adopt and implement a range of initiatives to manage emissions from sources they control, as well as indirect emissions from power generation and the broader value chain (Farsan et al., 2018).

In recent years, the literature has witnessed a surge in studies exploring corporate strategies for managing carbon emissions (e.g., Doda et al., 2016; Dietz et al., 2018; Cadez and Czerny, 2019; Zhou and Wen, 2020). These studies have proposed classifications of strategies, often with a conceptual focus. For instance, Cadez and Czerny (2019) categorized climate change mitigation strategies into internal carbon reduction, external carbon reduction, and carbon compensation. Similarly, Zhou and Wen (2020) classified carbon-constrained business strategies into internal emissions abatement, collaborative emissions abatement, and carbon compensation. Lee (2012) identified essential carbon management activities, including emission reduction commitments, product development, process and supply chain enhancements, organisational engagement, and external relationship development. Irrespective of these classifications, existing research recognises that, from an internal perspective, companies need to implement low-carbon operations, including initiatives related to product innovation (Böttcher and Müller, 2015; Zhou and Wen, 2021). Additionally, practitioner-oriented studies are emerging, highlighting that achieving GHG reduction targets involves innovation in business models, engagement with the value chain and consumers, product and service innovation, and the development of new operating policies, among other aspects.

However, despite these studies shedding light on "what needs to be done" by companies and the potential carbon management strategies they can employ, there remains limited empirical evidence regarding which initiatives companies have actually put into practice. Specifically, in the realm of product innovation, despite its recognition as a strategic avenue for reducing GHG emissions, empirical evidence on how products have been modified or updated, the product design approaches and measures adopted to address carbon emissions throughout a product's lifecycle, remains scarce. The literature on low-carbon product design has also expanded over the last decade, focusing largely on proposing carbon footprint models to provide quantitative evaluation metrics and guide GHG emissions reduction during product design decision-making (He et al., 2015). The literature has introduced methods for integrating carbon footprint estimation into design tools (Song and Lee, 2010; Qi and Wu, 2011; He et al., 2015). However, most of these studies are theoretical, and empirical evidence on how companies have effectively reduced GHG emissions across a product's lifecycle through design remains limited.

Therefore, this empirical-based study is dedicated to identifying design measures adopted by companies worldwide committed to GHG emission reduction through the adoption of science-based targets. The objective is to explore which design measures have contributed to emission reduction across different stages of a product's lifecycle. The findings seek to respond to the current calls in the corporate carbon management literature for further research and guidelines on translating greenhouse gas reduction targets into practical actions within companies (Wade and Rekker, 2020) by offering empirical evidence of how product design can influence and contribute to carbon footprint reduction. These calls for further research also emphasize the need for investigations exploring strategies and practices from an operational standpoint (Jabbour et al., 2021). Ultimately, the findings contribute to the low-carbon product design literature by offering empirical evidence of design measures adopted in practice that contribute to emission reduction across various phases of a product's lifecycle. This contribution is especially significant as existing low-carbon product design studies have predominantly remained theoretical, with limited insights into real-world company practices and clear evidence of how product design can effectively lead to emission reduction.

2. Theoretical background

A prominent focus in existing studies concerning corporate carbon management has centred on the formulation of classifications for climate change management strategies. In essence, these strategies can be regarded as initiatives aimed at mitigating the impact of business operations and securing enduring competitive advantages (Damert et al., 2017). Table 1 provides a summary of key classifications of corporate strategies for climate change management found in the extant literature, identified through a search for papers on corporate carbon management strategies.

From an empirical perspective and concerning the application of these proposed strategies, most existing studies have primarily concentrated on identifying groupings of companies that adopt similar strategies and/or on discussing strategies at a broader level. However, limited evidence exists regarding the actual operational changes made by businesses in response to climate risks and opportunities, encompassing alterations in operations, processes, products, services, and supply chain management, for instance. For instance, Kolk and Pinkse (2005) categorised companies based on their chosen strategies but did not delve into the specific actions undertaken by these companies in relation to each strategy. Similarly, Jeswani et al. (2008) identified energy efficiency-related operational activities in various sectors across two countries but did not explore the diverse array of changes with respect to processes or products that companies could implement. Yunus et al. (2016) associated product innovation strategies with the design of new, lower-carbon-emitting products or the enhancement of existing ones, yet they did not provide intricate insights into how new and/or existing products could be improved or which design approaches could be harnessed in the creation of novel, low-carbon products. In fact, comprehensive examinations of product innovation measures and practices aimed at reducing GHG emissions remain scarce within this realm of literature (e.g., Zhou and Wen, 2021). Therefore, when it comes to empirical

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evidence related to initiatives for product improvement and/or development approaches, the existing literature remains wanting.

Table 1. Summary of strategies for climate change management and terms used

Term used	Scope of categorization	Reference
Strategic options for climate change	Internal (organisation), vertical (supply chain), horizontal (beyond the supply chain)	Kolk and Pinkese (2005)
Corporate climate change strategies	Operational activities for energy efficiency and activities to reduce and manage greenhouse gases	Jeswani et al. (2008)
CO2 strategies	CO2 offset, CO2 reduction, carbon independence	Weinhofer and Hoffmann (2010)
Low-carbon operating practices	Low-carbon products, low-carbon production, and low-carbon logistics	Böcher and Müller (2015)
Carbon management practices	Intra-organisational carbon management practices, inter-organisational carbon management practices	Lee and Klassen (2016)
Carbon management strategies	Product innovation, innovative technologies, process innovation, energy efficiency initiative, participation in emissions trading, carbon offset initiative	Yunus et al. (2016)
Climate change mitigation strategies	Internal carbon reduction, external carbon reduction, carbon offset	Cadez and Czerny (2016)
Corporate carbon strategies	Carbon governance, carbon reduction, carbon competitiveness	Damert et al. (2017)
Carbon constrained business strategies	Reduction of internal emissions, collaborative reduction of emissions, carbon offsetting	Zhou and Wen (2021)

2.1. Low-carbon product design

Another strand of literature, the domain of sustainability-driven design, has delved into the carbon footprint of products throughout their lifecycles and emphasised the pivotal role of the design phase in crafting products with a reduced carbon footprint (e.g., He et al., 2015; Zheng et al., 2021). Indeed, a substantial portion of a product's carbon footprint is established during the design phase of its lifecycle (He et al., 2015). Consequently, studies have emerged, focusing on the quantification of the carbon footprint to furnish metrics for assessment and the development of product alternatives with diminished carbon footprints (e.g., Jeswiet and Kara, 2008; Ameta et al., 2009; He et al., 2015).

Another category of studies has centred on refining design processes and decision-making to yield reductions in carbon footprint (He et al., 2015). Numerous methods for integrating carbon footprint estimation into design tools have been proposed in prior research (Devanathan et al., 2010; Song and Lee, 2010; Kuo, 2013). Table 2 encapsulates select studies from the extant literature on low-carbon design, encompassing models for carbon footprint estimation and the integration of such estimation into the design process. A Scopus database search using the term "low-carbon design" yielded 200 articles, with some of these papers addressing specific application contexts, such as building design and mechanical and electrical products, while others offer generic insights applicable to the design of various products.

Despite the burgeoning body of literature on low-carbon design and the proliferation of methodologies and tools facilitating carbon footprint estimation and its integration into the design process, empirical evidence concerning the practical actions of companies and the overall design measures adopted in

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lower-emission products remains relatively scarce. Existing literature has predominantly focused on proposing theoretical models for carbon footprint estimation and/or methods and tools to support design. These studies often furnish examples of the application of their proposed methods or concentrate on specific application contexts.

Many companies have made commitments to science-based targets for reducing GHG emissions and have taken tangible steps to innovate their products and reduce emissions. However, empirical evidence regarding the practical actions of these companies remains limited. Understanding what companies are actively implementing, what has proven effective, and what can be developed further from a theoretical standpoint for practical application is invaluable.

Table 2. Some of the main low-carbon product design studies

Focus of the study	Reference
Propose a low-carbon product design system that allows quick calculation of the GHG emissions of a product. Thus, a designer can easily and quickly evaluate alternative parts for the design of a low-carbon product.	Song and Lee (2010)
Estimate the carbon footprint of dairy production systems through partial life cycle assessment.	Rotz et al. (2010)
Assesses the environmental impact of the commonest packaging options on the Spanish market for juice, beer and water.	Pasqualino et al. (2011)
Analyse the energy-saving features, drive mechanism and operating mechanism of modular design, and design a low-carbon 'products – technology' dynamic configuration application model following the modular design rules,	Qi and Wu (2011)
Offer a model with which the management and monitoring of emissions over time at the level of the individual product can be facilitated.	Scipioni et al. (2012)
Construct a collaborative design framework to help enterprises collect and calculate products' carbon footprints in a readily and timely manner throughout the entire supply chain.	Kuo (2013)
Propose a feature-based carbon footprint element model is proposed to estimate the carbon footprint at each stage of product life cycle.	He et al. (2015)
Modelling product carbon footprint for product life cycle under uncertainty.	He et al. (2019)

3. Methods

An inductive and case-based approach was utilised to discern the principal initiatives and design measures employed by companies in their practical efforts to address carbon emissions throughout a product's lifecycle.

The initial step involved identifying companies that had undertaken modifications to their products, encompassing both existing and newly developed items, as part of their business strategies to attain established science-based targets. Selection criteria were based on companies committed to GHG emissions reduction, having established targets, and providing reports to the Carbon Disclosure Project (CDP). The CDP, a non-profit organisation overseeing the global climate change reporting system, boasts participation from over 80% of the world's 500 largest companies. It is widely regarded as the most credible source of data on carbon management practices (Doda et al., 2016). Companies submit climate change reports to the CDP, which are made available for public review. Insights into emission management practices adopted by companies are gleaned from these reports.

The Science Based Targets initiative (SBTi), operating on an international scale, empowers companies to set ambitious emission reduction targets rooted in the latest climate science. SBTi's mission is to

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expedite global corporate action, with the aim of halving emissions by 2030 and achieving net-zero emissions by 2050, thereby propelling the global economy towards these pivotal milestones. As a founding partner of SBTi, CDP plays a crucial role in promoting the widespread adoption and integration of science-based target setting as the global standard of excellence.

Initially, the climate change reports for the year 2022 from 8,371 companies spanning various sectors and geographical locations were considered for analysis. Data supplied by companies in response to question 3.3 of the report, pertaining to how climate risks and opportunities influenced their product and service strategies, was examined. Among the initially considered 8,371 reports and companies, some indicated that the question was not applicable to them, while others submitted reports in languages other than English or left the question unanswered. These were subsequently excluded from the sample, resulting in a sample size of 4,147 companies and corresponding reports.

Subsequently, a content analysis was conducted to identify the primary design initiatives and measures articulated by companies as part of their product innovation efforts. ChatGPT played a pivotal role in identifying companies that mentioned design initiatives while explaining their product innovation strategies. It was employed for keyword extraction, which involves identifying and extracting essential words or phrases from text. This facilitated the distillation of critical information from companies' responses to CDP question 3.3, which was subsequently analysed by the research team.

ChatGPT was recognised as an invaluable tool in helping pinpoint core concepts in the data, with the responsibility of organising this material into a more coherent narrative resting with the researcher (Morgan, 2023). Among the 4,147 reports analysed, 1,815 companies were found to mention initiatives and design measures. The data analysis process adhered to the methodology for coding data outlined by Gioia et al. (2013). The design initiatives and measures highlighted in the reports were identified, coded, and subsequently aggregated according to the phases of the product lifecycle that they support in terms of emissions reductions. Figure 1 provides an overview of the steps undertaken in data collection and analysis.

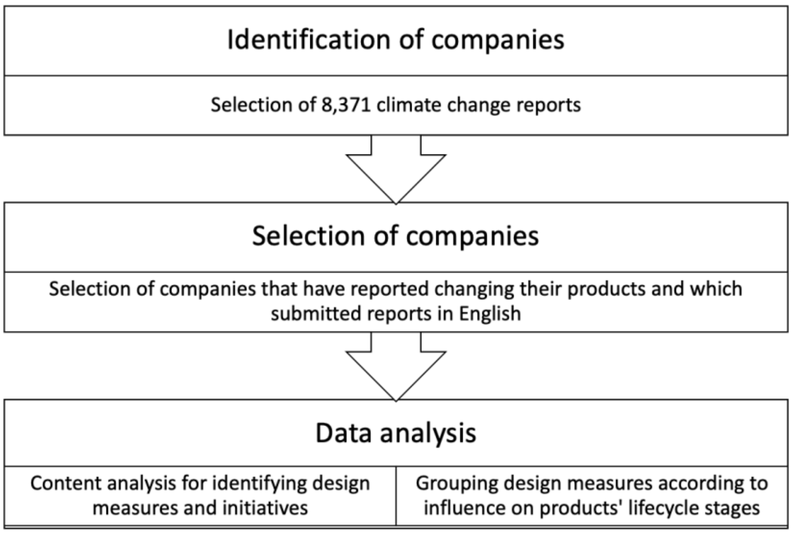

Figure 1. Steps followed for data collection and analysis

4. Design initiatives and measures to reduce emissions across products' lifecycle

The design stage plays a decisive role in creating low-carbon products. Design measures such as a product's weight reduction can reduce energy consumption and emissions in the use phase (Jeswani et al., 2008; Böttcher and Müller, 2015). The initiatives considered in the design process and design measures employed by the analysed companies were identified and categorised based on the product's lifecycle stage they apply to, i.e., the respective phase of a product's lifecycle that the measure employed during design contributes to reducing emissions, as summarised in Table 3 and detailed next.

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Table 3. Design measures employed by the analysed companies

Products' lifecycle phase impacted by design measures	Design measures to reduce emissions during the lifecycle phase	Examples of companies adopting the measures
Materials extraction and processing	Choosing recycled and recyclable materials (circular material utilisation)	Thermo Fisher Scientific Inc., C-Pack, HOOGERMAN ROMPA, China Everbright Environment Group Limited, The Kraft Heinz Company, Turtle & Hughes, ustries Pvt Ltd
	Weight reductions in materials	Granges Ab, W.R. Grace & Co.
	Design for reusing waste materials	Olvi Oyj, Grendene AS, Formosa Chemicals & Fibre Corporation
	Design for reducing material use	BENTELER Automotive
	Changing packaging materials	Össur hf., Hostess Brands
	Optimising the use of recycled material	Norsk Hydro ASA
	Choosing alternative lower carbon footprint materials	Chime Communications, Chicony Electronics Co. Ltd, Toyo Ink SC Holdings Co., Ltd., ELECOM CO.,LTD.
	Material process efficiency	Adler Pelzer Group
	Reducing material waste in production	Nordson Corporation
	Use of high-strength materials	Unipres Corporation
	Using lighter weight materials	CHALLENGE MFG CO, YANFENG, Aritzia Inc., GONVARRI Industries
	Shortening production process materials	IWASE COSFA CO.,LTD.
Manufacturing	Design for remanufacturing	Quadient AS, Deere & Company, Quadient AS
	Design of less emitter processes and improving manufacturing process	KISWIRE Ltd., MAVİ GİYİM SANAYİ VE TİCARET A.Ş., BAROQUE JAPAN LIMITED, Dubai Aerospace Enterprise
	Design energy efficient processes	Cooper Standard Automotive, Biocon, BAROQUE JAPAN LIMITED
	Design for reducing manufacturing energy requirements	Avient
	Choice of enhanced manufacturing process technologies	Compass Minerals International Inc, Wabtec Corp., Morgan Advanced Materials, Senior Plc
	Determinations in manufacturing sequence	ILJIN GLOBAL CO LTD
	Design for minimising resource use in manufacturing	Vitec Group Plc
	Design for reducing manufacturing waste	Stryker Corporation
	Design for extended product life	Deceuninck NV, Sika Group AG

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Use	Lightweight design	KLA, Companhia Brasileira de Alumínio, JAMCO CORPORATION, Thrace Group, Tokai Rika Co., Ltd.
	Specification of more energy efficient systems/subsystems	Harro Hofliger, KLA, Plastic Omnium
	Design for low energy consumption	VESTEL BEYAZ EŞYA SANAYİ VE TİCARET A.Ş., Acbel Polytech Inc, CAE Inc.
	Lightweight packaging design	Verallia, (ACIP) Alexandria Company for Industrial Packages
End-of-life management	Easy dismantling design	Pegatron Corporation
	Design for recovery	Pegatron Corporation, Lenzing AG
	Design for reuse, repair, recycling	Ambipar Participacoes e Empreendimentos, Adobe, Ingka Holding B.V., Aoyama Trading Co., Ltd., Natura Cosmeticos AS, Ambu AS, Nipro Corporation, Reynders Label Printing
	Lightweight design	Thrace Group, Koluman Otomotiv Endustri A.S., Adeka Corporation, Cleveland-Cliffs Inc.
	Use of recycled and recyclable materials	Norsk Hydro ASA, Winpak Ltd., Mondelez International Inc
	Design for disassembly	CNH Industrial NV

The analysed companies highlighted changes in the current product development process to incorporate GHG emissions into decision-making. Those include the implementation of ecodesign rules not previously employed (e.g. Natura Cosmetics, Gerresheimer AG, LVMH) tools for estimating emissions, adoption of design for environment and design for sustainability approaches (e.g. Merck & Co., Inc., Logitech Europe S.A.), as well as design for circularity (e.g. Ingka Holding B.V., PUMA SE, DS Smith Plc). Some companies also mentioned implementing circular design training, new ecodesign programmes and establishing new ecodesign principles. Around 250 companies in the sample mentioned modifications in their current design process to address emission reduction targets.

Design measures related to reducing emissions in material extraction and processing/manufacturing were identified for around 350 companies. The choice of alternative materials with lower emissions and recyclable and recycled materials cut emissions related to the extraction/processing of new material. Design optimisation to reduce the quantity of material used in products and/or optimising the use of recycled material also reduces emissions related to material extraction/processing. Companies have considered other measures when reflecting on materials during design, including creating materials passports and investing in research and development of new materials.

Design choices regarding manufacturing methods, sequences, process engineering and production systems contribute to emissions in the manufacturing phase. Design measures that allow the reduction of carbon emissions during production identified in the sample include

the estimation of manufacturing energy consumption and design of more energy-efficient processes, choosing new technologies and emission reduction equipment when engineering the manufacturing of the products and production systems, and making efficient choices when designing the manufacturing methods and process (e.g. non-acid manufacturing process, additive manufacturing).

Waste reduction in manufacturing through specifications of processes and systems was also identified. Design for minimising resource use in manufacturing and design for remanufacturing is also relevant to cutting emissions associated with manufacturing a new component. Designing products with an extended life also reduces emissions related to manufacturing new products and materials extraction and processing. The emissions generated in the use of the product by the consumer are related to the time of operation in use and the lifetime of the product. The average energy consumption is associated with the emissions and takes into account the product lifetime and consumed electricity. Thus, the design of products that consume less energy or energy efficient use designs cut down emissions in the use phase.

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Measures in this sense include reducing the weight of products (which also contributes to reducing emissions related to distribution) and design specification of more energy efficient systems/subsystems (e.g. focusing on aerodynamic performance).
The recycling methods of the recyclable materials and parts and the disposal methods for the remaining waste, for example, depend on the type and weight of the materials of each part of a product. Thus, design decisions about the materials used in the products and dimensions of the products will also impact on emissions for recycling and disposing the products at the end of life. Additionally, how much energy will be employed in recovering processes will also depend on the products' project, and products designed for disassembly, remanufacturing, reuse and recycling will respectively lead to less emissions for processing at the end of life. Embedding circular principles into design can contribute to reduce emissions at the end of life and also in other stages of the product lifecycle. Nonetheless, only 52 companies in the sample reported incorporating circular principles into design.

4.1. Discussion and conclusions

The data analysis conducted in this study has unveiled a spectrum of initiatives and design strategies currently being implemented by companies to reduce emissions throughout product lifecycles. These efforts play a pivotal role in enabling these organisations to meet their science-based targets for emissions reduction. However, it is noteworthy that only a minority of companies in the sample have reported such measures. This does not imply a lack of innovation in their design processes or a deliberate omission of emission-reducing strategies, but rather a gap in the reporting mechanisms. These unreported measures remain obscured from secondary data analyses, presenting a limitation to the full understanding of how companies are innovating their products for a lower carbon footprint.
Despite this limitation, the insights gained are invaluable, illuminating the practical initiatives undertaken by companies to integrate design into product innovation for a decarbonised economy. The findings enrich the existing body of literature by demonstrating how practical design measures contribute significantly to the reduction of lifecycle emissions. The evolution of design literature has been remarkable, offering a plethora of sustainable methodologies—ranging from eco-design and design for the environment to design for circularity and sustainability. These approaches underpin the reduction of greenhouse gas emissions and the minimisation of carbon footprints during the design phase.
Nevertheless, there is a discernible fragmentation within these initiatives in current literature, a noticeable disconnect between evidence of practical application by companies and an overarching guidance or integrated approach that consolidates all methods to support the design of products for a low-carbon economy. This study represents an initial foray into gathering data and comprehending the practical actions companies are taking in this direction. It marks the beginning of ongoing research into the development of a Design for Low-Carbon Lifecycle (DfLCL) concept that synthesises existing theoretical design methods with practical applications.
The results from this study will serve as foundational inputs for future research, which will explore the DfLCL concept more deeply. This will include the development of a comprehensive framework that aligns with design literature and supports the crafting of the next generation of products tailored for a low-carbon economy. The aim is not only to bridge the gaps identified but also to offer a cohesive blueprint that can be adopted by companies seeking to innovate responsibly within the parameters set by the exigencies of climate science.

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