Journal of Circular Economy (2025) 3:3, 491-513
https://doi.org/10.55845/IRVU6231T2026

RESEARCH ARTICLE

Implementation of Circular Design Principles in Industrial Product Development

Pruhs, A.[1*], Kusch, A.[1], Bezerra de Araujo, J.[1], Hummen, T.[2], Mendgen, R.[2], Viere, T.[1], Woidasky, J.[1]

Received: 27. May 2025 / Accepted: 18. November 2025 / Published: 8. December 2025
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Abstract:

The transition to a Circular Economy is a key driver of sustainable development and requires the design of circular products, services and business models at the industrial level. However, current product design and Circular Economy approaches often lack holistic integration from the strategic to the operational level, limiting the full implementation of circular strategies. This paper addresses the urgent need for an integrated approach that makes general circular economy guidelines fully operational by providing detailed design principles to optimize circularity and sustainability outcomes throughout the product life cycle, from raw material sourcing to end-of-life. Because the practical implementation of circularity in industrial product development processes is not a relevant subject of current research and publications in the circularity domain, this paper conceptualizes a comprehensive Design for Circularity approach. By demonstrating the interaction between Circular Economy Business Models, Ecodesign Approaches, and specific product life cycle intensities, this study introduces a decision support method tailored to industrial product development processes. The key result of this study is a proposed solution list, presenting circular design principles in a structured solution matrix. This matrix provides tailored practical guidelines which are directly applicable in industrial product development. By operationalizing circularity for industrial design processes, this paper not only addresses an existing research gap, but also provides a comprehensive decision support tool for circular design. Moreover, this approach enables the quantitative assessment of circular solution paths from strategic planning down to the product structure level, thus promoting the effective implementation of circularity in industrial practice.

Keywords Industrial Ecology · Circular Economy · Design for Circularity · Circular Design Principles · Product development process · Product Design

1. Introduction

The linear production model, grounded in abundant resources and inexpensive energy, is coming to its end, as environmental challenges intensify, resources diminish, consumption escalates, and externality costs pressures society and governments (Bocken et al., 2016). Consequently, the concept of Circular Economy (CE) has been promoted by authors from different areas of knowledge (Korhonen et al., 2018), brought together by a shared vision of an economic system where resources remain circulating, and their value is maximized over time, instead of being discarded, along with their inherent value. In this system, CE aims to accomplish sustainable

*Corresponding Author: Annika.Pruhs@hs-pforzheim.de
1 Institute for Industrial Ecology, Pforzheim University, Pforzheim, Germany
2 Corporate Research and Advance Development, Robert Bosch GmbH, Renningen, Germany

development by decoupling resource use and environmental impacts from economic prosperity and well-being. Among theorists and practitioners, CE is growing in relevance, as it is accepted as an operationalization of sustainable development within companies (Kirchherr et al., 2023). According to Kirchherr et al. (2017), the most recognized definition for CE was formulated by the MacArthur Foundation: "A CE is an industrial system that is restorative or regenerative by intention and design." (Ellen MacArthur Foundation, 2013, p. 7). It opens a multidisciplinary field that brings together different approaches, methods, and tools (Mendoza et al., 2017).

Following Pigosso & McAloone (2021), companies face difficulties to successfully implement CE, due to its systemic nature, high complexity, high risk, multi- and intra-disciplinarily, in addition to a general lack of knowledge. Furthermore, statistical figures like the global circularity rate of only 7.2% in 2023 described in the Circularity Gap Report (Circle Economy, 2023) indicate that the practical implementation of CE is still in an early stage.

An effective transition to CE at the company level depends on two critical elements: innovative business models and circular product design practices (Eisenreich et al., 2022; Uhrenholt et al.; 2022). Business model innovation is pivotal for enabling the transition to CE, as it creates opportunities for the efficient use of resources across multiple cycles, minimizes waste and material consumption, and ultimately contributes to the preservation of material and product value over time (Geissdoerfer et al., 2018; Lüdeke-Freund et al., 2019; Gusmerotti et al, 2019). Recent research underlines that the maturity of circular business models within firms is a decisive factor for effectively implementing CE strategies in practice (Lang et al., 2025). Bocken et al. (2016) emphasize here that the successful adoption of CE principles by companies largely depends on the evolution of product development practices, as implementing changes becomes significantly more difficult once product specifications are finalized.

Therefore, product development for circular economy (PDCE) considerations have become an important topic in research on CE (Reslan et al., 2022). The European Green Deal, for instance, designates product design as one of the three priority areas for the development and implementation of CE practices (European Commission, 2022).

According to Aguiar & Jugend (2022), PDCE it is a new area with growing academic relevance, but without a detailed approach for the inclusion into companies' product development process (PDP). Baldassarre et al. (2020) conclude that PDCE needs to expand to become a multi-area, systemic and integrated process, which helps product designers moving away from just being operational product makers.

Considering that PDCE aims to disrupt the linear chain paradigm and to explore novel approaches for generating economic value, it becomes evident that product design inherently relies on novel business models. Bocken et al. (2016) explain that product business models shift from generating profits through the sale of artifacts to generating profits from the flow of materials, products, and services over time. The significance of such business model has been explored by Diaz et al. (2021), whose research revealed business model innovations concerning topics such as sources of revenue and intended customer base. While the product's business model is located at strategic level, its implementation at the operational level requires specific competencies. Ecodesign is meant to support CE in product design and development (Yriberry et al., 2023; Riesener et al., 2023) and to align operational decisions with the strategic circular business models perspective. Riesener et al. (2023) notice that the implementation of ecodesign involves an ambidextrous approach encompassing both product design and business model.

Recently, efforts have been undertaken to modernize the ecodesign framework to incorporate CE elements, such as in the EU ecodesign Directive (Polverini, 2021). Its purpose is to design products capable of being reintegrated into the production cycle as either products or materials, thereby aligning with CE objectives. This approach aims to minimize negative impacts by adding value to waste (Yriberry et al., 2023). The array of ecodesign tools within PDCE may be part of *Design for X* (DfX) strategies, e.g. design for disassembly. The selection of appropriate tools in the product development decision-making process should regard both the intrinsic properties of the product and the associated business model. While DfX approaches are considered a useful approach to operationalize circular business models (Aguiar & Jugend, 2022), the extensive array of ecodesign tools and methods coupled with a large range of business model options requires guidance on selecting suitable combinations (Rousseaux et al.; 2017). As a consequence, companies might limit themselves to a number of well-known approaches instead of making use of the entire spectrum of options (Diaz et al., 2021).

Although several DfX methodologies currently exist, their implementation can pose significant challenges. Much has been written about Design for Manufacture and Design for Assembly, which both aim to reduce design and production costs. However, today the concept has expanded to encompass "Design for X", where X may stand for areas such as maintenance, the environment, reuse, disposal, recycling or even the entire life cycle (Colin et al., 2020). Additionally, Design for Reliability (DfR) emphasises considering reliability aspects early in the design process to minimise unexpected failures, improve safety and reduce maintenance and life cycle costs (Go et al., 2015). Some methodologies have already integrated DfX with CE Business Models (CBM). However, a notable gap remains: A comprehensive approach that incorporates the identification of environmental impact hotspots, a decision support system (Grünig & Kühn, 2013), and, critically, an emphasis on the more detailed phases of product design is still missing. Building on this, the present research makes an advance in the field by developing a coherent framework that integrates the various dimensions of the circular economy, resulting in technical design recommendations for products. The framework reduces complexity and enhances transparency by systematically combining these decision-making elements. It also provides practitioners with structured guidance to help them align product design choices with circular economy objectives. In doing so, it operationalises Design for Circularity (DfC) at the intersection of product-level design decisions and company-level business model strategies. This offers theoretical progress through conceptual synthesis and practical relevance by enabling firms to implement circularity in everyday design activities.

The structure of this paper is as follows: Chapter 2 lays the foundation by reviewing the state of the art in circular product development approaches and identifying the research gaps that need to be addressed. Building on these insights, Chapter 3 introduces the methodological framework developed to integrate Circular Design Principles into industrial product development. This framework provides the basis for Chapter 4, where the results are presented, including the derivation of principles and their systematic mapping to Ecodesign Approaches. Finally, Chapter 5 connects back to the previous findings by discussing their theoretical contributions and practical implications, and by outlining avenues for future research.

2. State of the Art

2.1. Circularity allocation in product development processes

A typical PDP consists of six sequential phases, as outlined in Figure 1. Beginning with the planning phase, it is followed by the concept development phase, collectively identified as the *early product design phases*. They involve essential activities like market research, technology development, and defining the product's form, function, and features. Subsequently, the process advances to the *detailed product design phases*, for a more thorough refinement, addressing elements such as design, architecture, and component specifications (Ulrich & Eppinger, 2015).

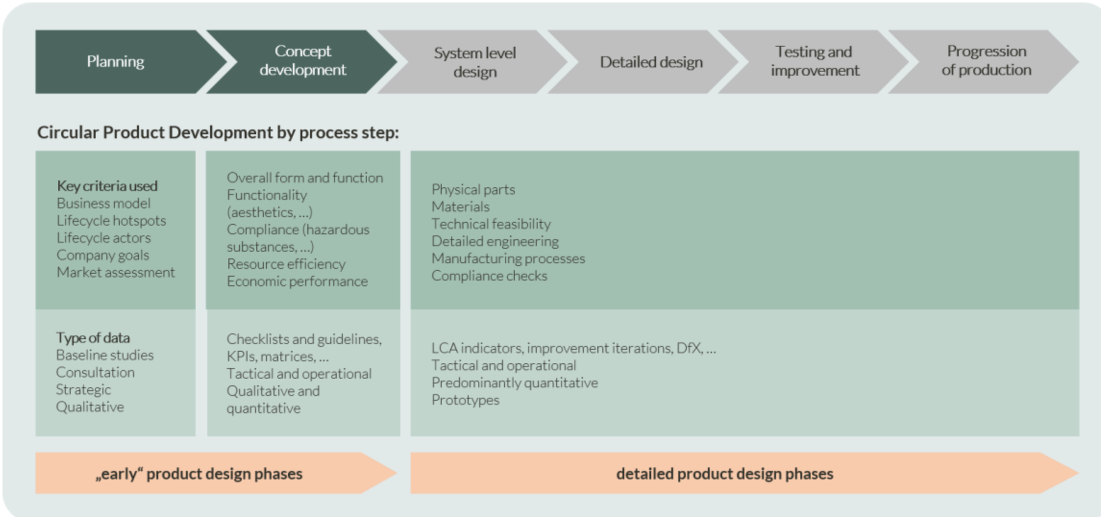

Figure 1. Circular design aspects in a typical PDP (*adapted from* Ulrich & Eppinger, 2015; Diaz et al., 2021).

The design of more circular products influences both the early and detailed design phases. The key distinction between these stages lies in their optimization focus: In the early phases, the priority is to identify critical aspects for the product's circularity performance (hotspots) and its business model. As the emphasis lies more on intangible aspects such as business models, or obtaining quantitative indicators, many models rely on qualitative analysis (Royo et al., 2023). The detailed design phase, in turn, aims to transform these general guidelines into specific product design specifications. It is predominantly technical and quantitative, so more structured decision support methods are used, e.g., Life Cycle Assessment (LCA) indicators (Diaz et al., 2021).

To comprehensively support CE, it needs to be integrated into the early PDP stages. Once the product concept is defined, making significant changes becomes challenging (Bocken et al., 2016). It is estimated that approximately 80% of the environmental impacts associated with products are typically determined during early PDP stages (European Commission, 2020). Identifying circular hotspots is one possible approach to integrate CE into early design stages (Albæk et al., 2020). However, this approach remains underutilized (Diaz et al., 2021). While decisions made during the early design phases significantly influence future performance, Royo et al. (2023) asserts that the proceeding phases should not be overlooked. It is noted that the current approaches for PDCE are concentrated in the two initial stages of the PDP, the planning and concept stages (Aguiar & Jugend, 2022).

2.2. Product Development Process Features

PDCE approaches in literature vary in terms of constitutive elements, integration into the PDP (early or detailed product design phases), and key outcomes (e.g., technical specifications). The constitutive elements may be condensed into five features as given in Table 1, including business models and strategies for a Design for Circularity (DfC) (feature 1), Ecodesign Approaches (EDAs) (feature 2), the identification of impact hotspots and opportunities for circularity improvement (feature 3), methods for integration and systematization (feature 4), as well as circular approaches that have an effect on the product structure during the detailed product design phases (feature 5).

A common feature among approaches in literature is their focus on design guideline lists aligned with predefined circularity strategies (feature 1 and 2). This approach provides a holistic perspective that considers not only the product directly, but also the significance of circular business models and their integration in the design process. It ensures that the design process is effectively aligned with the chosen business model (Moreno et al., 2016, Shahbazi & Jönbrink (2020).

Considering feature 3, namely the influence of various circular and operational optimisation measures on the PDP, the level of integration varies. Some approaches offer comprehensive solutions, supporting decision-making (Pruhs et al., 2024; Mendoza et al., 2017), while others are lacking further integration with product life cycle impact assessments (Moreno et al., 2016; Aguiar & Jugend, 2022) However, it is crucial to consider the broader potential impacts of the proposed product, service, or business model during the concept generation phase. Failing to address feature 3 may lead to circular product design solutions that are merely palliative, thereby increasing the risk of rebound effects (Saari et al.; 2024).

Mendoza et al. (2017) employ LCA to identify circular *hotspots* in PDCE approaches. However, complexity and data requirements of LCA often restrict its application to later PDP stages, when the product architecture is more developed (Diaz et al., 2021). This is corroborated by Mendoza et al. (2017), acknowledging the complexity of LCA and the need for simplified methods incorporated in the PDCE. Pruhs et al. (2024), instead of using an LCA to identify circular hotspots, employ the simpler approach "Life Cycle Intensity" (LCI) to support decision-making. LCI conceives that products typically cause significant environmental impacts in only one or a few phases of their life cycle (e.g. in manufacturing only), enabling the clustering of products according to their specific hotspots.

Table 1. Comparison of research approaches for an operational DfC based on selected features

This research approach…	**Feature 1** Considers CE strategies that contribute to the circularity of products.	**Feature 2** Includes consideration of the Ecodesign requirements of the current EU Directive. (European Commission, 2022.)	**Feature 3** Includes the influence of various circular and operational optimisation measures on the PDP.	**Feature 4** Provides the user with a methodical decision-making aid as to which measures make sense for circular optimisation	**Feature 5** Includes circular solution approaches that have an effect on the product structure.
Moreno et al. (2016); Shahbazi & Jönbrink (2020)	Yes.	Yes.	No.	No.	No.
Mendoza et al. (2017)	Yes.	Yes.	Yes.	No.	No.
Pruhs et al. (2024)	Yes.	Yes.	Yes.	Yes.	Introduced

Moving to feature 4, it is uncommon for PDCE approaches to incorporate decision-support methods specifically aimed at facilitating circular optimization. Notably, Pruhs et al. (2024) employed a decision tree in combination with matrices to represent all possible relationships among the three proposed dimensions CBM, EDA, and Life Cycle Intensity (LCI) impact hotspots. This approach was used to identify the bilateral combination of elements in a matrix format, to identify circularity approaches for a given product. Based on literature, expert consultations and workshops, the matrices were arranged in a decision tree (Figure 2). (Kotsiantis, 2013)

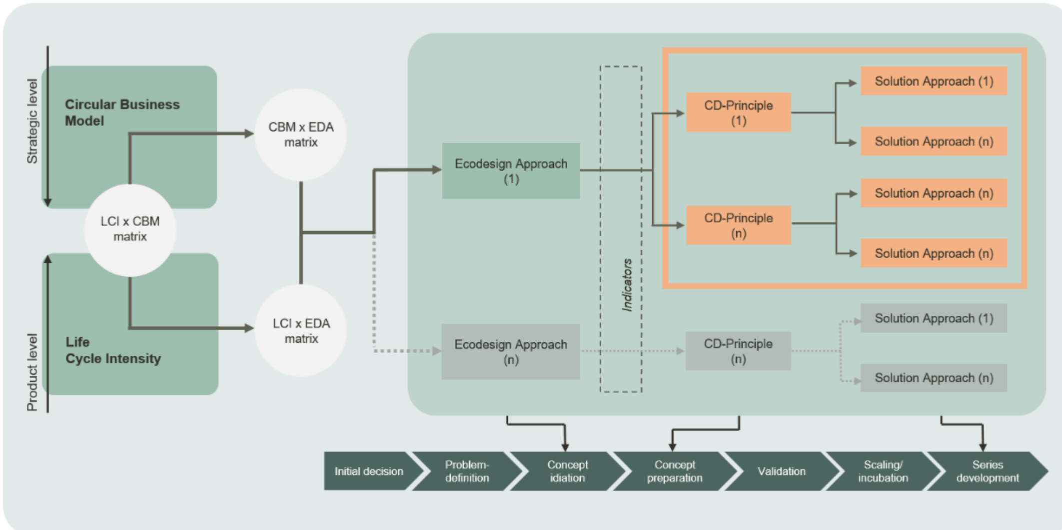

Figure 2. DfC decision-making process (schematic) for industrial PDP (Pruhs et al., 2024).

In the Pruhs et al. (2024) approach, circular design starts with the LCIxCBM matrix, where the circularity contribution of a CBM for a specific product is assessed alongside its environmental properties determined by its LCI, offering a prioritization of the CBM. In sequence, the CBMxEDA matrix then supports the identification of the most suitable design approaches. Alternatively, if a business model (CBM) has been agreed upon as a first step of the design process, the LCIxCBM matrix and LCIxEDA matrix are applied to determine suitable EDA for the given CBM. Both paths result in a targeted list of selected Circular Design Principles (CDPs) for the specific decision setting. Examples for CDPs are described the model decision-making in Pruhs et al. (2024). However, a comprehensive methodological framework for systematically investigating and structuring circular solutions that impact product architecture (feature 5) has not yet been established.

2.3. Research gap

The prevailing PDCE approaches rely heavily on generalised and generic circular product design guidelines, highlighting the need for more detailed and actionable CE design principles (den Hollander et al; 2017; Lucrezia et al; 2025). This gap is particularly evident at the detailed design stage, where specific and actionable guidelines are essential to achieve higher levels of circularity and sustainability. Polverini (2021) and Riesener et al. (2023) state that literature lacks both a systematic review of CE design principles within Ecodesign, and an accessible, practical framework for industrial application. Furthermore, current tools aimed at embedding CE design principles in PDCE are often criticized for their complexity and resource-intensive nature (Rossi et al., 2016). These tools often require extensive contextual knowledge and impose significant time constraints that limit their practical applicability in industrial settings.

Furthermore, literature lacks an integrative approach that systematically incorporates circular design strategies aimed at influencing the product structure (feature 5) (Kreutzer et al., 2023). To enable circular product evolution especially in the detailed design phase, it is essential to methodically develop CDPs and derive corresponding action-oriented recommendations. As current PDCE methodologies are mainly applied in the early stages of the PDP and focus mainly on planning and conceptual design, none of the five existing PDCE approaches (Table 1) provides concrete solution strategies that directly influence or modify product structures to improve circularity.

To address these shortcomings, a holistic and integrated PDCE framework is proposed here, with higher granularity throughout the product design process. This approach extends beyond the initial design stages by incorporating detailed CDPs into the later, more complex stages of product development where critical design decisions are finalized. By systematically embedding Design for Circularity (DfC) into industrial product development, this framework aims to reconcile the need for detailed CDPs with practical feasibility, ensuring their actual application in industrial contexts.

3. Methods

To address the research gap, a structured solution framework that systematically integrates and operationalises CDPs within PDCE is being developed. The proposed approach synthesises insights from established theoretical frameworks in literature with empirical findings from expert consultations and industry collaborations. By extending PDCE approaches beyond the early design phases into the detailed product development stages, this study fills a critical research gap and provides a structured and actionable approach for the effective implementation of circular product design principles.

The core of this methodological approach is the systematic formulation and categorization of CDPs, designed to bridge the gap between conventional product design methodologies and the specific requirements of circular product development. A central element of this framework is the development of a solution matrix, which allocates CDPs to overarching fields of action and simultaneously provides targeted, practical design strategies that can be directly integrated into industrial PDPs. This development of the methodological framework builds on the earlier work of Pruhs et al. (2024), which fulfils all the criteria outlined in Table 1 and thus provides a comprehensive basis for addressing the challenges identified.

The relationship between circularity strategies, corresponding CDPs and their industrial application is discussed in detail in the following sections. By using a literature- and expert-based compilation of validated circularity principles, this study presents a user-centered tool that overcomes the limitations of existing approaches and facilitates the systematic integration of circularity into future product designs.

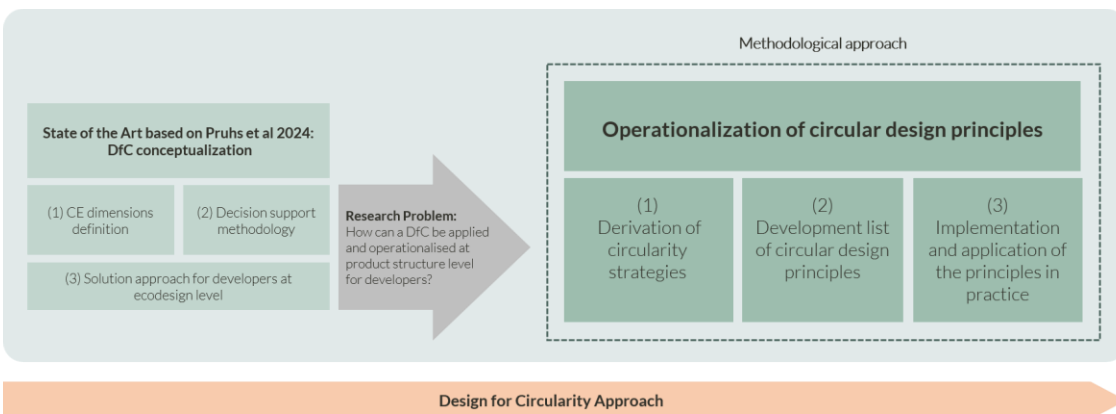

Figure 3. Method to conceptualize and operationalize a design for circularity within PDPs (Authors' Work).

The focus of this study lies on the operationalization phase of the tool (shown in Figure 3), using CE design principles for this purpose. By detailing these methods, the following chapter aims to provide a comprehensive understanding of how CDPs can be operationalized within product development, ensuring that circularity is embedded into the very fabric of new products and business models.

To address the identified research gap, a structured four-step approach was undertaken:

First, circularity strategies were derived (1) through a comprehensive literature review and systematic organization of CDPs.

In the second step, a detailed list of CDPs was developed (2) by mapping them to established EDAs. This was followed by an expert evaluation of the resulting CDP×EDA matrix and a visual representation of different solution approaches along two different decision paths, illustrated by product examples.

The proposed methodology was then evaluated and validated in an industrial context to ensure its practical applicability (3).

The evaluation was binary; a maximum of 3 EDAs were assigned per solution approach to ensure prioritisation. In total 104 solutions were assigned.

The comparison and categorisation of the CDPs based on the EDAs was carried out by a panel of experts, based on the nominal group technique of Potter et al. (2004) and Harvey and Holmes (2012). The group consisted of a total of twelve representatives from business and academia, and CE topics from the literature were progressively assessed based on the experts' expertise. All experts were selected from institutions involved in a research project on the CE funded by the German government (see Acknowledgements).

Finally, the methodological approach was classified and critically discussed to assess its contribution to the advancement of circular design strategies and its implications for future research.

4. Results

4.1. Derivation of circularity strategies from mechanical engineering

The technical principles known from literature, such as functional or assembly-oriented design (Bender and Gericke, 2021), serve as a starting point for the development of a circularity-oriented guide for product developers. The research hypothesis was that circularity is largely determined by technical product characteristics as well as other factors, such as the usability of a product (Tischner and Moser, 2015). In addition, further solution approaches were investigated and developed in cooperation with companies from the manufacturing industry. The result is a set of CDPs that can be applied in product development, combining classical design principles with elements of user design and ecological approaches. The list of CDPs (cf. Table 2) can be read from left to right as the level of detail increases. The cluster of areas for action allocates CDPs to groups, just as individual approaches are assigned to the CDPs. CDP Definitions are also provided.

Table 2 below shows an extract from the CDP list; the full list is available as supplementary material in the Appendix:

Table 2 List Part of the list of CDPs with subdivisions: Fields of Action, CDPs, Definition of Term, Solution Approach.

Areas of Action	CDPs	CDP Definition	Solution Approach
functionality	functional durability	The functional durability of a part or product describes its ability to function as required under specific conditions of use, maintenance and repair until a limited condition is reached (DIN EN 45552:2020-05)	Make the wear condition as easily and clearly recognizable as possible to be able to assess wear stock or reusability.
			Manage wear and equip the product with diagnostic and/or auto-diagnostic systems for serviceable components that indicate product or component status, e.g. tire pressure monitoring.
			Develop a core of components/parts in the product that are not subject to wear and tear and can be reused.
			Arrange components that represent a function so that they can be reused or replaced as such.

The different levels of detail of the CE principles examined require a suitable categorisation. As a first step, the results of the literature reviews were assigned to a total of 9 fields of action that reflect the key areas of influence in manufacturing technology:

- The field of action groups together various areas of design theory, such as functional design, and provides an overarching category for all related technical principles (Bender and Gericke, 2021). Functionality, for example, includes CDPs that improve the functionality of products to minimise design flaws that affect how the product is used. They also enable the extension of functionality by upgrades or updates.

Within the fields of action, further design principles can be learned from construction, but also from sustainable product development or user experience. These are called CDPs. A total of **34 CDPs** provide key technical requirements for implementing circularity in the product, which are directly applied in the PDP.

- The CDP is defined as a set of design and technical principles that can increase the circularity of products and thus intervene in the product structure. They are formulated in a general way so they can be applied in different forms and for different product categories with different solutions, for example with regard to the functional durability, which describes the ability of a part or product to function as required under specific conditions of use, maintenance and repair until a limited state is reached (DIN EN 45552:2020-05).

The application of a CDP can be interpreted differently depending on the product case. For example, for the technical principle of functional durability (DIN EN 45552:2020-05), the ability to function as required under certain conditions of use, maintenance and repair until a limited state is reached, wear can be directed to specially designed, easily adjustable or replaceable elements (Bender and Gericke, 2021). For example, by using a brushless motor instead of a brush motor, components can be used that are subject to less wear and can be reused. However, the focus can also be on wear detection alone, so that wear can be controlled by diagnostic and/or auto-diagnostic systems for serviceable components, e.g. by targeted selection of friction pairings.

In order to demonstrate various possible applications, the CDP level is detailed in a further solution level. For the generic solution approaches, various application examples, currently **104**, have been identified from literature and are now available for the user as a call to action:

- The solution approach describes various technical options per CDP to implement the design principle. Using the example of the CDP *functional durability*, visualising wear or preventing wear can help to ensure the function of the product. At this point, there are several approaches that can be supplemented as required and can also differ depending on the product. For this reason, descriptions based on specific product examples for the purpose of clarity and comprehensibility have been added. The solution approach is always to be understood as a direct request to the developer and formulated in this way, e.g. "Identify and reinforce mechanically stressed areas".

Depending on the level of knowledge and product maturity, one or more solution approaches will be selected. Several individual solutions can be selected, or a whole CDP cluster can be applied. Alternatively, a specific problem in the product structure can be solved with a targeted solution approach. As a prerequisite, each proposed solution has been assessed to determine whether it contributes to the promotion of circularity. This assessment is particularly important for purely technical solutions.

The fields of action and the associated CDPs are deliberately formulated in a general a manner as much as possible. The solutions, on the other hand, are exemplary and in some cases product-related. The information provided by the list should be supplemented in companies by company-specific information such as material comparison lists, durability assessments, or information on the availability of recyclates. If necessary, the proposed solutions can be prioritised by the development team, e.g. by comparing them in pairs using circularity criteria. It is therefore possible to customise the list and adapt it for transfer to individual companies.

4.2. Mapping of Circular Design Principles to Ecodesign Approaches

The previous operationalisation of CE strategies and business models using a decision tree in Pruhs et al. (2024) allows the developer to prioritise circular business and environmental information in a simple and systematic way (see chapter 2.2). The decision tree provides recommendations tailored to individual products and business models. At the product level, at the end of the decision tree, the designer can consider a selection of Ecodesign requirements. These are then linked to the list of CDPs to provide the user with a systematic selection of appropriate recommendations for action (see Figure 3).

A section of the full CDPxEDA matrix (Table 3) is showing the systematic mapping of CDPs and associated solutions to selected Ecodesign requirements. The highlighted area describes the assignment of an Ecodesign requirement to the corresponding solution approach of the CDP *functional durability*. The full table is available in the annex.

Table 3. Visualisation of a Circular Design Principle with assigned solution approaches in relation to Ecodesign requirements. (excerpt, full table available as Supporting Information S1) A solution approach marked in grey applies to the respective Ecodesign approach and supports its application.

Circular Design Principles (CDP)	Title of solution approaches	Solution approaches	Ecodesign Approaches												
			durability	reliability	reusability	upgradability	reparability	possibility of maintenance and refurbishment;	presence of substances of concern;	energy use or energy efficiency	resource use or resource efficiency	recycled content	possibility of remanufacturing and recycling;	possibility of recovery of materials;	expected generation of waste materials
functional durability	Recognizable wear	*Make the wear condition as easily and clearly recognizable as possible to be able to assess wear stock or reusability.*		■				■							
	Limited wear	*Limit wear, e.g. by applying hard or seal coatings.*	■	■				■							
	Auto-diagnostic systems	*Manage wear and equip the product with diagnostic and/or auto-diagnostic systems for serviceable components that indicate product or component status, e.g. tire pressure monitoring.*		■				■		■					
	Stability analysis	*Increase stability by stability analysis of all parts, e.g. by balance points.*	■	■							■				
	Corrosion resistance	*Increase corrosion resistance, e.g. by smooth surface design, material selection and wall thickness allowance against evenly and largely uniformly abrading corrosion, butt welds or through-welded fillet welds, sealing, moisture protection against crevice corrosion, by low potential differences of the metal components and sealing against electrolytic action to prevent contact corrosion.*	■	■	■										

Table 3(Cont.). Visualisation of a Circular Design Principle with assigned solution approaches in relation to Ecodesign requirements. (excerpt, full table available as Supporting Information S1) A solution approach marked in grey applies to the respective Ecodesign approach and supports its application.

Circular Design Principles (CDP)	Title of solution approaches	Solution approaches	Ecodesign Approaches												
			durability	reliability	reusability	upgradability	reparability	possibility of maintenance and refurbishment;	presence of substances of concern;	energy use or energy efficiency	resource use or resource efficiency	recycled content	possibility of remanufacturing and recycling;	possibility of recovery of materials;	expected generation of waste materials
functional durability	Core components	*Develop a core of components/parts in the product that are not subject to wear and tear and can be reused.*	■	■	■										
	Components arrangement	*Arrange components that represent a function so that they can be reused or replaced as such.*			■		■	■							
	Service life	*Plan the service life of replaceable components according to a planned time span.*	■	■											

The results of the solutions assignment to EDA is shown in Figure 4. The EDA *Maintenance and Refurbishment* has the most assigned solution approaches with 42 and can therefore be implemented in numerous ways. *Repairability* ranks second with 29 assigned solutions, followed by *remanufacturing and recycling* with 27. The fulfilment of these EDA is therefore particularly diverse, making their implementation comparatively easy. The solutions within a CDP have not been prioritised though, even if some may be very specific or less applicable than others. This may be carried out in a later step of research, or during customization of this approach for company-internal processes.

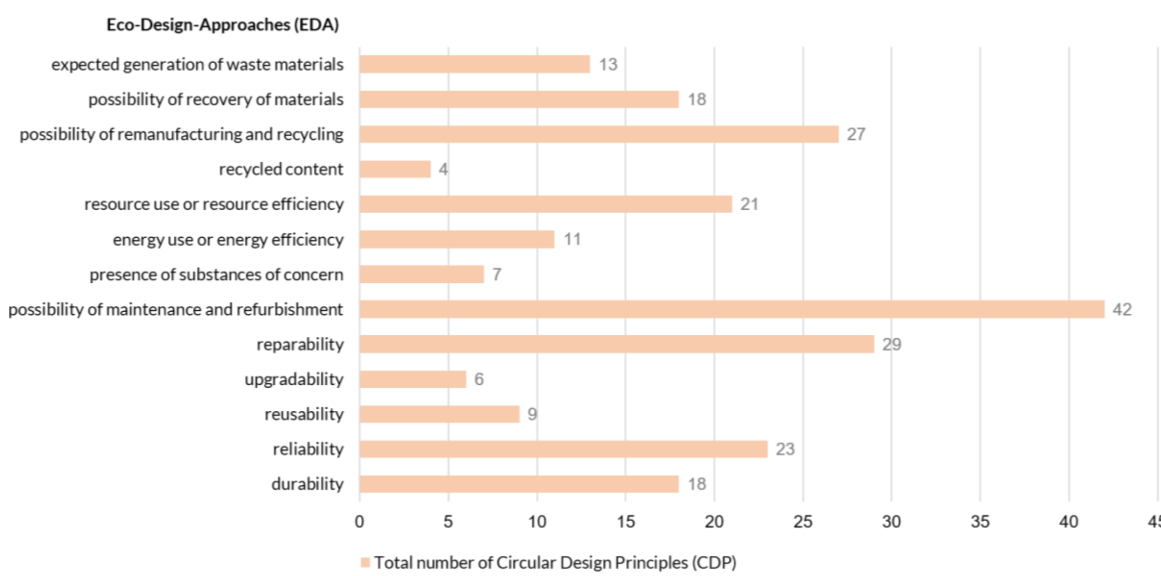

Figure 4. Diagram illustrating the total number of CDPs per EDA (Authors' Work)

The method presented so far will now be applied as an example to explain the practical application of the CDP list. In order to compare the different results of this prioritisation process, different use cases are compared in Table 3. On the one hand, two different CBMs are applied to an example product, an impact drill, and on the other hand, the path for two products with different LCIs (production-intensive: 1. impact drill, 2. blender) is applied on the basis of one CBM. The decision methodology provides the developer with a list of prioritised EDAs depending on the environmental classification of a product or business model choice. This in turn identifies prioritised CDPs in the EDA x CDP matrix at a constructive level for direct implementation in the product development process.

A comparison of already fulfilled EDAs and CDPs and a subsequent selection of the most suitable or most promising EDAs and CDPs from the existing prioritisation must be carried out on a case-by-case basis by experts in industrial product development, as they are directly related to the requirements of the selected products and company policy.

Table 4 demonstrates the practical application of the proposed decision-making methodology, comparing two products — an impact drill and a blender — under different decision paths. It shows how the selection of Circular Design Principles (CDPs) depends on the identified Life Cycle Intensity (LCI) and the chosen Circular Business Model (CBM), as filtered through the CDP×EDA matrix. Presenting these scenarios side by side provides an exemplary execution of a decision path as it could occur in industrial product development. This highlights the adaptability of CDPs to different products and strategies, and underscores the practical applicability of the framework by showing how circular solutions can be derived and implemented systematically in real-world design processes.

Table 4. Visualisation of the results of different solution approaches following two decision paths using product examples.

Decision path sequence	Product example 1 IMPACT DRILL	Product example 2 BLENDER
ENTRY DECISION PATH	***PRODUCT LEVEL (New product/ further development) OR STRATEGY LEVEL (Business model development)***	
DECISION 1	***PRODUCT LEVEL***	
Use Case Two products have been selected and described here as examples of the decision path.	An impact drill is characterised by the fact that it generates an additional vibration in the axial direction in addition to the conventional rotary movement. The aim is to make an existing product more circular at a technical level based on the existing product architecture. The decision-making process starts at product level. As the impact drill is classified as manufacturing-intensive (Holzhausen and Troedsson, 2023), the manufacturing phase can be used as an entry point for the LCI x CBM matrix (Pruhs et al., 2024).	A blender or stand mixer is an electrical kitchen appliance that is used to mix liquid or semi-solid ingredients or to blend food. The aim is to make an existing product more circular at a technical level using the existing product architecture. The decision-making process starts at product level. As the blender is classified as manufacturing-intensive (Hawthorne and Ameta, 2021) manufacturing phase can be used as an entry point for the LCI x CBM matrix (Pruhs et al., 2024).

Table 4(Cont.). Visualisation of the results of different solution approaches following two decision paths using product examples.

Decision path sequence	Product example 1 IMPACT DRILL		Product example 2 BLENDER
ENTRY DECISION PATH	**PRODUCT LEVEL (New product/ further development) OR STRATEGY LEVEL (Business model development)**		
DECISION 2	**MANUFACTURING INTENSIVE PRODUCTS**		
Filtering through LCI x CBM matrix This classification filters business model fields with circular properties using the LCI x CBM matrix.	For products that require intensive manufacturing, the business models remanufacturing, reuse and digitalisation are suitable. (Pruhs et al., 2024)		
DECISION 3	**REMANUFACTURING**	**REUSE & REDISTRIBUTION**	
Characterisation CBM	For this path, we consider the remanufacturing business model, which is characterised by extending the useful life and increasing functionality by remanufacturing used products and components as well as maintenance and repair services and is also applied to the impact drill. (Lüdeke-Freund et al., 2018)	For this path, we consider the reuse business model, which is characterised by extending the useful life and increasing functionality through preventive maintenance and repair services. (Hansen et al., 2020; Lüdeke-Freund et al., 2018)	
Filtering using the CBM x EDA matrix In the next step, the CBM x EDA matrix is used to identify Ecodesign Approaches that are compatible with the selected business model. For each of the examples shown here, 3 EDAs are selected in the next step.	5 EDAs are filtered for the successful implementation of the circular business model Remanufacturing: Presence of substances of concern, Energy use/efficiency, Maintenance and refurbishment, Resource use/efficiency, Remanufacturing and recycling. (Pruhs et al., 2024)	7 EDAs are filtered for the successful implementation of the circular business model Reuse: Reparability, Reusability, Maintenance and refurbishment, Reliability, Energy use, Resource use, Durability. (Pruhs et al., 2024)	
DECISION 4	**RESOURCE USE, MAINTENANCE AND REFURBISHMENT, REMANUFACTURING AND RECYCLING**	**REPARABILITY,** **REUSABILITY,** **MAINTENANCE AND REFURBISHMENT**	**RELIABILITY, RESOURCE USE/EFFICIENCY,** **REUSABILITY**
Filtering through EDA x CDP matrix The application on a technical level takes place through the CDPs.	For business model remanufacturing using the product example impact drill, 22 CDPs were filtered for the 3 selected EDAs. For business model reuse using the product example impact drill, 18 CDPs were filtered for the 3 selected EDAs. For business model reuse using the product example blender, 20 CDPs were filtered for the 3 selected EDAs. For the product example, 1 already fulfilled and 2 open CDPs were listed as examples and explained in more detail below (see Supplementary Material).		

Table 4(Cont.). Visualisation of the results of different solution approaches following two decision paths using product examples.

Decision path sequence	Product example 1 IMPACT DRILL		Product example 2 BLENDER
ENTRY DECISION PATH	**PRODUCT LEVEL (New product/ further development) OR STRATEGY LEVEL (Business model development)**		
DECISION 5	**NON-DESTRUCTIVE DISASSEMBLY, CIRCULAR MATERIAL SELECTION, FUNCTION EXPANSION**	**FUNCTION EXPANSION, USE OF STANDARDIZED PARTS, FUNCTIONAL DURABILITY**	**FUNCTIONAL DURABILITY RESOURCE-EFFICIENT MATERIAL INPUT, ERGONOMIC DESIGN**
Fulfilled CDPs These CDPs have already been fulfilled for the product example and do not need to be optimised further at this point.	The principle of non-destructive disassembly, which is already implemented on the product, for example, through non-destructive connections, is one of the ways in which the EDA Remanufacturing and Recycling is realised (VDI-Norm 2343, 2009).	The reparability of a product can enable reuse (DIN EN 45554:2020-10). This can be implemented through a product architecture that, for example, allows the additional provision of replaceable components during the use phase (Bender and Gericke, 2021). Technical measures such as the use of standardized parts and the modularisation of the product can support this (Moss, 1985), e.g. by using the same types of screws or standardised carbon brush sets.	To maintain functional durability and to use the product in a defined operational state for as long as possible (DIN EN 45554:2020-10), the blender has an intelligent thermal management system. An auto-diagnostic system such as the preventive temperature monitoring (overload protection) of the drive components prevents interruption of use and can support the reliable function of a product.
Open CDPs: These CDPs have not yet been fulfilled for the product example and therefore offer circular potential for improvement.	By circular material selection, scarce, hazardous or environmentally harmful raw materials are replaced by materials based on raw materials that are available for longer (Bender and Gericke, 2021). Recycled materials can be used for the housing of the impact drill, or materials that are difficult to recycle, such as glass fibres and multi-material composites, can be eliminated from the handle of the impact drill (DIN 45557:2020, 2020)	Potential for improvement lies in stress-resistant materials. To extend the utilisation phase and enable reuse, it makes sense to use robust materials (Andrzejewski et al, 2024). Ideally, components are used that are subject to low wear and can be reused, e.g. by using a brushless motor (Pfeffer, 2013).	To save weight during transport, the thermoplastic polyester Tritan can be used for the mixing container instead of borosilicate glass (Reuter, 2014). This is also heat-resistant, lightweight and shatterproof, as well as recyclable, thus ensuring resource-efficient input of primary raw materials (VDI-Norm 4800 Blatt 1, 2016).
	In addition, a functional expansion offers opportunities for comprehensive refurbishment (Lüdeke-Freund et al., 2018) This can be achieved through the use of standardised components or the upgradeability of the impact drill. Optional functions that can be added include an integrated spirit level, a line finder or automatic angle measurement for optimum drilling results.	The aim of the EDA Possibility of maintenance and refurbishment (DIN EN 45554:2020-10) is a longer service life during which the product is available in a defined operational condition. The technical principle of functional durability can be applied to maintain this condition (DIN EN 45552:2020-05). For the application of the reuse business model, it would be useful to measure the state of wear, e.g. by using an operating hours counter, in order to calculate forecasts for the maintenance of functional durability and to provide possible spare parts.	Ergonomic design is the design and arrangement of things used by people so that people and things interact as efficiently and safely as possible. (Merriam-Webster, 2016). It can ensure extended product use and can have a positive impact on increasing its reusability. An ergonomic design could be achieved through active noise cancellation. With the help of a product-specific noise cancelling app, an anti-phase noise is generated, thereby reducing the overall noise for the user.
Result based on various solution options	**CIRCULAR OPTIMISED PRODUCTS**		

In the decision-making logic, the EDAs *maintenance* and *energy use* are filtered for the *reuse* and *remanufacturing* business models in both cases. Non-destructive and easy dismantling capability plays an important role for maintenance and repair in particular and is relevant for the product-side implementation of both business models. Differences can be seen, for example, in the increased durability and longevity of the entire product function for an extension of the utilisation phase within a reuse business model compared to the stronger focus on the material level within the remanufacturing strategy. Here, the reusability of components and materials and the simple replacement of components are prioritised.

By applying the *Reuse* business model to the impact drill and the blender, similar EDAs are identified in each case. In addition to the selection of different CDPs, the CDP *functional durability* was analysed for both products. As *functional durability* is fundamental to the implementation of the reuse business model (Hansen et al., 2020; Lüdeke-Freund et al., 2018), it was applied to both products. In the case of the impact drill, the optimisation of wear diagnostics can contribute to functional durability, whereas the functional durability of the blender is already ensured by preventive temperature monitoring. The selection of the applied EDAs differs due to product-specific properties. Which CDPs are relevant, already fulfilled or offer potential for improvement depends on the respective product properties. As shown here using the example of functional durability, the CDP for the impact drill offers opportunities for optimisation, whereas the CDP for the blender has already been fulfilled so comprehensively that other CDPs can be prioritised. Individual prioritisation of the CDPs in the company's own product development is therefore recommended, even if they overlap for different products, as here the decision tree's logic ends and expert discussion becomes necessary.

There is not just one suitable solution for increasing product circularity, but different solutions can be filtered through the decision-making methodology and applied individually depending on the product and business requirements.

4.3. Method implementation and validation in an industrial context

Circular business and product design is not common in manufacturing companies, although there is some experience with specific products such as remanufacturing of car parts or repair of power tools, as in the case of Bosch (Robert Bosch GmbH, 2023). Looking ahead, factors such as legislation, OEM requirements and end-customer expectations are driving sustainable and circular design, and the company has already taken this into account by developing a sustainability and circularity strategy with accompanying measures to implement sustainable and circular product design.

These measures include the implementation of sustainability expert roles in all Bosch business units, the development of roadmaps for the use of more sustainable materials, the empowerment of employees throughout the PDP towards more sustainable design, and the provision of appropriate development tools. CDPs, as described in this paper, are a core element of the enabling measures and supporting tools. Recognizing this at an early stage, Bosch experts compiled literature on sustainable design, reviewed available training courses on learning platforms and collected experiences and good practices from early adopters within the company and contributed these to a body of knowledge. The holistic view enabled a comprehensive implementation of CDPs for all relevant EDAs and circular business models, as described in this paper. The company-specific implementation consists of a set of web-based trainings to teach numerous employees in the PDP, as well as a guideline document with the same content for reference and for those who prefer document-based learning.

Evaluated by the previous application framework it can be state that the implementation

- has a high comprehensiveness,
- explains and considers circular economy business models with their consequences on product design,
- fosters Ecodesign by providing a wealth of generic guidelines as well as practical examples from different business units of the company for inspiration,
- introduces simple tools for hotspot identification that can be used by any employee at any time in the PDP, but also explains LCA as an expert method for more complex cases and official reporting.

The information is freely available on the company's learning portal and document repository, and the web-based training courses can be attended by any employee without prior authorization from a line manager to minimise implementation barriers. The information is disseminated through presentations at internal conferences, presentations to relevant working groups, articles in the company portal or mentions in the official sustainability report. In addition, training is becoming a mandatory part of the curriculum for an increasing number of roles in the PDP, from product management to engineering or production planning.

As a next step, Bosch intends to provide a web-based implementation of the developed body of knowledge on the Bosch learning portal, in order to offer users an even more convenient interface and a more problem-specific selection of relevant Ecodesign principles and guidance. In addition, Bosch is working on implementing the guidelines directly into its product development systems, such as CAD, for automated checks and improvement suggestions. Here the prototypes are still at a very early stage and not yet suitable for practical implementation. In parallel Bosch is working on the implementation of circularity knowledge in development processes and regulations, but the focus lies strongly on enabling and supporting the workforce. Requirements for sustainable or circular design are already becoming increasingly important, and their fulfilment will be checked anyway in the stage-gate PDPs, but the workforces' knowledge to achieve this will be the decisive factor.

5. Discussion and Conclusion

This study's theoretical contribution lies in the development of a systematic framework that facilitates the integration of circularity into product structures and the PDP. Leveraging existing product characteristics, the solution matrix presented in this study (extract in Tables 2 and 3 and full version in the appendix) enables decision-makers to derive tailored design recommendations, thereby operationalising DfC. The framework builds upon the decision logic outlined by Pruhs et al. (2024) and can also be applied independently to support circular product development. While numerous circular product design approaches are documented in the literature (Mendoza et al., 2017; Moreno et al., 2016; Shahbazi & Jönbrink, 2020), a comprehensive and structured framework that systematically integrates key decision-making elements has remained absent (Mestre & Cooper, 2017). In particular, no existing approach has been identified that brings together all essential circular product design components—CBMs, EDAs, LCIs and CDPs. Moreover, prior research has primarily focused on the early stages of PDP, such as planning and conceptualisation, with limited insights into later phases such as engineering and detailed design (Aguiar & Jugend, 2022). Addressing this gap, the present study makes a decisive contribution by proposing a novel framework that integrates these decision-making elements across the PDP. A key finding is that, despite the wide variety of circular design approaches available, companies often restrict themselves to a limited number of familiar strategies. The methodology presented here addresses this challenge by reducing complexity and providing structured guidance to support informed decision-making and the wider adoption of circular economy principles. The importance of such decision support is emphasised by Rousseaux et al. (2017), who argue that firms require clear guidance when selecting ecodesign tools, and by Saari et al. (2024), whose multiple case studies demonstrate that structured matrices can successfully guide manufacturing companies in their transition towards circularity. The interdisciplinary development of the proposed approach, incorporating insights from both academia and industry specialists, further enhances its robustness and practical relevance. By systematically integrating CBMs, EDAs, LCIs and CDPs into a coherent framework, this research advances conceptual clarity and bridges the gap between systemic circular economy goals and product-level design requirements. In doing so, it also aligns with international standards such as ISO 59010 and ISO 59040, thereby reinforcing both its scientific and industrial significance.

In practical terms, the study provides industry practitioners with a structured foundation for implementing circular product design strategies. Although a wide range of circular design approaches exists, companies often rely on a limited set of familiar strategies and fail to explore the full spectrum of available options. This tendency is linked to the overwhelming number of potential measures and the complexity of decision-making processes (Diaz et al., 2021). The methodology developed in this study addresses this challenge by streamlining the selection process, reducing complexity, and lowering implementation barriers. The 104 CDPs created offer targeted recommendations that can be directly integrated into PDPs by adapting or aligning existing business models with specific product characteristics. Their structured nature simplifies application, improves usability and supports informed decision-making. Integrating circular design strategies early in the development process maximises their impact, and continuous evaluation throughout the PDP ensures flexibility and responsiveness. Translating methodological insights into digital tools, such as the Circularity Navigator (Kusch et al., 2024), is another step towards practical applicability. This makes circularity accessible to non-experts and reduces methodological complexity. Validation in industrial contexts has confirmed the usefulness of these tools and the necessity of sector-specific adaptations and illustrative best practice examples. These findings align with those of Saari et al. (2024), who emphasise that structured tools and matrices enhance transparency and strengthen organisational confidence in adopting circular strategies. Ultimately, the CDPs and associated tools provide engineers and designers with actionable knowledge, embedding circularity principles into everyday product development.

Nevertheless, several limitations of the research must be acknowledged. The methodology relies on predefined solution paths, which may limit its applicability in contexts where specific solutions are already in place or require further adaptation. The quantification of trade-offs depends heavily on the availability of appropriate indicators. While some strategies have established metrics, others remain difficult to measure. Additionally, the semi-quantitative scoring methods employed are inherently subjective, even when consensus-building techniques such as the Nominal Group Technique (Potter et al., 2004; Harvey & Holmes, 2012) are utilised. Furthermore, most validations were conducted within relatively narrow product domains, raising questions about transferability across industries. Finally, while the developed frameworks are intentionally generic to ensure broad applicability, this reduces their sensitivity to sector-specific regulations and value-chain characteristics. This means they require additional contextualisation by individual companies.

Building on these insights, several avenues for future research emerge. The CDP framework should be further developed to include quantitative assessment methods based on key performance indicators, enabling more robust evaluation of trade-offs. Aggregated scores or benchmarking systems could enable companies to position their products within a broader performance landscape. The systematic integration of ecological and economic perspectives is an urgent priority, given that current approaches largely treat these dimensions separately (Velenturf & Purnell, 2021). Promising developments include linking CAD environments with life cycle assessment and techno-economic analysis modules to enable the real-time evaluation of design alternatives (Tao et al., 2018). Furthermore, future research should expand validation efforts through sector-specific case studies to ensure broader applicability. It should also explore the co-evolution of design methods, business models and systemic enablers, such as repair infrastructures, reverse logistics and user engagement. Finally, organisational readiness, including adjusted KPIs, resource allocation and staff training, will continue to play a decisive role in successfully implementing circularity.

In conclusion, this research demonstrates that operationalising Design for Circularity requires a structured interplay of conceptual synthesis, practical tools, digitalisation and quantifiable assessment. By bringing these elements together in a coherent framework, the study makes a valuable contribution to both academic discourse and industrial practice. It offers companies a scientifically sound yet practical approach to incorporating circularity into product development, thereby accelerating the transition towards a circular economy.

Acknowledgments The authors thank Robert Bosch GmbH, the German Research Center for Artificial Intelligence GmbH/Smart Enterprise Engineering, and iPoint-systems GmbH for their constructive and pleasant cooperation. Special thanks go to the project partners for their valuable suggestions and beneficial discussions. The DfC-Industry project is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) and supervised by Project Management Jülich (FKZ 03EI5005A). The exclusive responsibility for this text lies with the authors. The journal thanks Helena Bahr for their administrative assistance throughout the publication process.

Funding Information The DfC-Industry project is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) (FKZ 03EI5005A) and supervised by the project management organization Jülich.

Author Contributions **Annika Pruhs:** conceptualisation, methodology, data curation, writing - original draft, Visualisation, Writing - review & editing **Anina Kusch:** conceptualisation, data curation, writing - original draft, Visualisation, Writing - review & editing **Juliano Bezerra de Araujo:** writing - original draft, Writing - review & editing **Torsten Hummen:** writing - original draft **Ralf Mendgen:** writing - original draft **Tobias Viere:** Funding acquisition, Writing - review & editing, Project administration and Supervision **Jörg Woidasky:** Funding acquisition, Writing - review & editing, Project administration and Supervision. All authors have read and agreed to the published version of the manuscript.

Data availability statement The data relevant to the paper can be found in the supplementary material enclosed.

Declarations

Competing interests The authors declare no competing interests.

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Supporting Information

Supporting Information S1: This supporting information provides a structured overview of circular design principles broken down into specific solution approaches. These approaches are systematically compared with established ecodesign requirements. For each requirement, the table assesses which solution approaches contribute to its implementation at product level. The resulting matrix highlights synergies between circularity strategies and ecodesign practices, providing a practical decision support tool for industrial product designers. It enables users to identify relevant circular solutions for specific design goals and assess their applicability across different product life cycle stages. The table thus facilitates targeted, sustainability-oriented design decisions in practice.

Figure Legends

Figure 1. Circular design aspects in a typical PDP (adapted from Ulrich & Eppinger, 2015; Diaz et al., 2021).

Figure 2. DfC decision-making process (schematic) for industrial PDP (Pruhs et al., 2024).

Figure 3. Method to conceptualize and operationalize a design for circularity within PDPs.

Figure 4. Diagram illustrating the total number of CDPs per EDA.

This manuscript has supporting information

Supporting information DOI: https://doi.org/10.55845/MBRQ4783