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Resilient Product Design: Effective Product Development for the Circular Economy

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Summary: Companies are currently facing the challenge of having to transform their linear approach to product design into a circular one in order to remain competitive. The reason for this is the increasing pressure in the supply of primary resources, consumer and employee expectations, as well as requirements of financial institutions and tightening regulation with regard to general environmental impacts. A standardized procedure for implementation of circular design in product development is not yet established. Based on an interview study focusing on the product development of manufacturing companies in German-speaking countries, this article summarizes the greatest challenges in the implementation of circularity in products and offers possible solutions for implementation of circular design.

Keywords: Product design, product development, product architecture, circular economy

Resiliente Produktentwicklung – kreislaufgerechte Produktarchitekturen für zukunftsfähige Produkte und Unternehmen

Zusammenfassung: Unternehmen stehen derzeit vor der Herausforderung, ihre lineare Herangehensweise an die Produktgestaltung in eine zirkuläre umwandeln zu müssen, um wettbewerbsfähig zu bleiben. Der Grund dafür ist der zunehmende Druck bei der Versorgung mit Primärressourcen, die Erwartungen von Verbrauchern und Arbeitnehmern sowie die Anforderungen von Finanzinstituten und die Verschärfung der Regulatorik im Hinblick auf Umweltauswirkungen. Ein standardisiertes Vorgehen zur Umsetzung von kreislaufgerechter Produktentwicklung ist noch nicht etabliert. Basierend auf einer Interviewstudie mit Fokus auf die Produktentwicklung produzierender Unternehmen im deutschsprachigen Raum fasst dieser Artikel die größten Herausforderungen bei der Umsetzung von kreislaufgerechter Produktentwicklung zusammen und bietet Lösungsansätze für die Implementierung von Circular Design.

Stichwörter: Produktdesign, Produktentwicklung, Produktarchitektur, Kreislaufwirtschaft

Despite setbacks in environmental regulation, the fundamental trend towards sustainability and circular products remains and is even intensifying due to increased environmental

risks.[1] Businesses, especially in the manufacturing industry, must therefore adapt their product design to the challenges of a fundamentally changing economic world. Product planning, conceptualization, and design, referred to as 'development phase', determine the majority of costs and environmental impacts over the entire life cycle of a product.[2] This is why the development phase in particular offers significant potential for increasing resource effectiveness and efficiency as well as reducing greenhouse gas emissions.

To reveal the current challenges in the development of circular products in industrial practice, a total of 35 qualitative interviews were conducted in the first half of 2024. The semi-structured interviews lasted 90–120 minutes each. The majority of participants in the study were product architects, product sustainability managers, circular economy managers, and CxOs from the specialist areas of product and series development, sustainability, as well as research and pre-development. The participating functions were predominantly managers such as managing directors and board members, division and department heads, and project leaders and managers with responsibility for sustainability and the circular economy. In particular, automotive industry OEMs and 1st tier suppliers, mechanical and plant engineering, and medical technology from countries of the DACH region are strongly represented among the interviewees.

	R-Strategies	Description
Smarter product use and manufacture	R0: Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1: Rethink	Make product use more intensive (e.g. by sharing product)
	R2: Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3: Reuse	Reuse by another customer of discarded product which is still in good condition and fulfils its original function
	R4: Repair	Repair and maintenance of defective product so it can be used with its original function
	R5: Refurbish	Restore an old product and bring it up to date
	R6: Remanufacture	Use parts of discarded product or its parts in a new product with the same function
	R7: Repurpose	Use parts of discarded product or its parts in a new product with a different function
Useful application of materials	R8: Recycle	Process materials to obtain the same or lower quality

Figure 1 R-Strategies according to Kirchherr[3]

The biggest barrier to be overcome to unlock the previously untapped potential of product development is a circular business model and the resulting targets as well as performance indicators for controlling the development process. Once a circular business model has been found, be it for a single R-strategy (see Figure 1) such as recycling, remanufacturing or refurbishment or a product-as-a-service model, the untapped potential of incorporating circular aspects in product development can be exploited. Car sharing models for example require a radical rethinking of how a car is designed: e.g. from a mileage of several hundred thousand kilometers to a few million kilometers.

1 World Economic Forum. Global Risks Perception Survey 2023–2024.
2 VDI Zentrum Ressourceneffizienz (2024). Produktentwicklung & ihr Einfluss auf Ressourceneffizienz. https://www.ressource-deutschland.de/themen/produktentwicklung/. Last checked: 15.11.2024.
3 Julian Kirchherr, Denise Reike, Marko Hekkert. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, Volume 127, 2017, Pages 221–232, ISSN 0921–3449.

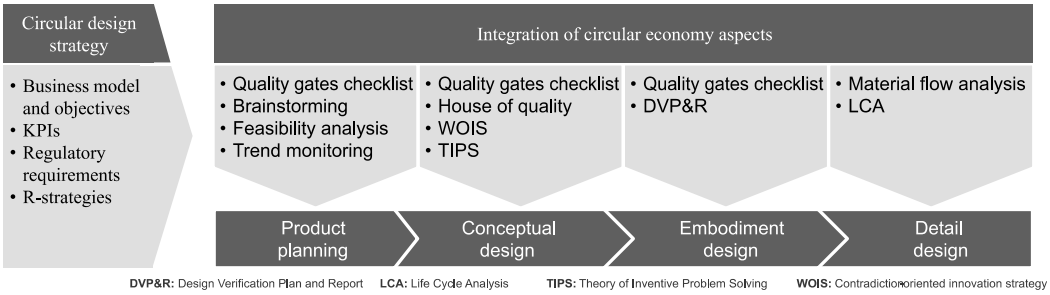

Figure 2: Potential methods used to integrate circular economy aspects in the product development process

But how to transition a highly standardized and well-established research and development (R&D) into the circular economy? Study results show that first ideas exist but no standardized approach to circular design has yet been established in industry (see Figure 2).[4]

Extending existing development processes, methods and tools to a circular approach with an update of quality gate checklists is crucial, but does not go far enough. In addition to the state-of-the-art product development principles of systems thinking, lean and agile, the design methodology must be supplemented by circular principles and practices. A systems engineering approach can be the solution for linking these aspects. This begins with defining clear targets based on double materiality and circular business model analysis at the very start of the development process, e.g.

- What are our material topics? These topics can be inside-out like pollution, emissions or high energy, critical material or water consumption as well as outside-in like climate risk impacts, scarcity of resources or new regulatory requirements.
- Which R-strategy is being pursued? Due to the specifics of the individual circular strategies, implementation must be evaluated individually in each case.
- How tight are the component and material cycles set? This means closing loops within a product, company, industry or even beyond.
- What are our hotspot materials? Specify which materials to be handled with specific care throughout product development like for example nickel, lithium or cobalt in electric mobility.

Integrating "Design-for-X" and other circularity criteria catalogs into the conceptual design phase, e.g. Design-for-Recycling, -Disassembly, -Upgradeability, etc. contributes to the more efficient implementation of circularity in the embodiment design phase. In addition, the following overarching circular architecture design characteristics must be considered throughout the phases of the product development process of future circular products:

- *Modularity:* Modular product architectures make the future products easier to disassemble. By defining clear interfaces, detachable and therefore circular connection technologies can be used in a targeted manner.

4 Pfletschinger, Stölzle, Kreimeyer. Study Report Resilient Product Design – Circular product architectures for future-proof products and companies. 2024.

- *Upgradeability:* Individual modules can be designed in such a way that they can be replaced if necessary and, in the best case, upgraded. In conjunction with an update of the product architecture, new functions can also be integrated into an "old" product.
- *Longevity:* Modular product architecture designed for the circular economy can have a major impact on the longevity of a product, which can be extended through upgradeability and functional enhancements.
- *Application-specific materials:* Reduction in the variety of materials. Use of monomaterials such as single-origin plastics and metals as well as biodegradable, renewable alternatives and secondary raw materials.

Monitoring the ecological impact and therefore the effectiveness of the circular product design in the form of a Life-Cycle-Assessment (LCA) not just in the detailed design phase at the end of development but from the early stages of development onwards is crucial. However, companies are currently still facing challenges in this regard due to a lack of standardized approaches and methods. Building the necessary data infrastructure maximizes the product life cycle through enabling adaptive closed-loop management with solutions like a virtual twin or a digital product passport to realize the full circular economy potential and build up a 'virtual mine'. Taking a holistic approach in circular product design integrating all aspects of sustainability like pollution, water and land use as well as biodiversity besides climate change and circularity in R&D marks the next step towards a nature positive product.

Pioneers of the circular economy are doing exactly that. Volvo car corporation for example uses a Life Cycle Impact Assessment (LCIA) method to assess the biodiversity footprint, following the ReCiPe model. ReCiPe is an established method using generic data for translating emissions and resource extractions into estimated environmental pressures including land use, water use, climate change, and different types of pollution. The ReCiPe model also converts these different types of impact into a single common metric, expressed in 'species.year.'[5]

In conclusion, transitioning to a circular economy is essential for reducing environmental impact and increasing resource effectiveness and efficiency. By incorporating circular principles and practices into the product development process, businesses can significantly improve sustainability, as demonstrated by pioneers of the circular economy. From an economic perspective, adopting circular product design can also lead to cost savings through reduced material waste, extended product lifecycles, and the potential for new revenue streams through services like product leasing or refurbishment. Embracing a holistic approach to design, with a focus on modularity, upgradeability, longevity and application-specific materials, not only supports long-term environmental sustainability but also fosters economic resilience by optimizing resource use and enhancing market competitiveness.

5 Volvo Car Corporation. (2024). Volvo Cars Position on nature and biodiversity [Press release]. https://www.volvocars.com/images/v/-/media/project/contentplatform/data/media/sustainability/volvo_cars_position_on_nature_and_biodiversity.pdfed: 15.11.2024.

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