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Design for Circularity (DfCE) – How to Align Product Requirements With R-Strategies to Enhance Circular Economy on an Operational Level

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Introduction

The circular economy has emerged as a pivotal concept in promoting sustainable development by redefining how resources are utilized, products are built and used, and waste is managed. Foundational to this concept is the framework of R-strategies (Refuse, Reduce, Rethink, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) (Potting et al., 2017) which serve as guiding principles towards adopting sustainability objectives. Understanding how each R-strategy influences product design, lifecycle, and end-of-life handling is crucial for aligning product development with circular economy goals. (Diaz et al., 2021) Product requirements, defined as the attributes necessary for meeting circular objectives, play a significant role in this paradigm shift. Key circular economy theories emphasize integrating R-strategies into product design, manufacturing, use, and value retention. (Ibid.)

This study aims to explore how R-strategies shape product requirements clustered in sub-categories (see figure 1), such as durability, reparability, and modularity, and to identify the role of design considerations in enhancing product circularity. Existing studies either focus on specific product or material groups (e.g., plastics, textiles, electronic devices, or composite fibers) (e.g. Berwald et al., 2021; Bovea & Pérez-Belis, 2018; circular.fashion UG, 2018; Joustra & Bessai, 2021), limiting their applicability, or are too generic for practical design processes (Diez, 2023; Earley & Politowicz, 2023; Shahbazi, 2023). They also lack a common definition of R-strategies and their sub-categories (Eberhardt et al., 2022), causing confusion when combining guidelines. Furthermore, the interconnections between sub-categories of design for circularity (DfCE) have not been thoroughly investigated, yet these interconnections are crucial for understanding how overlapping and complementary strategies can enhance

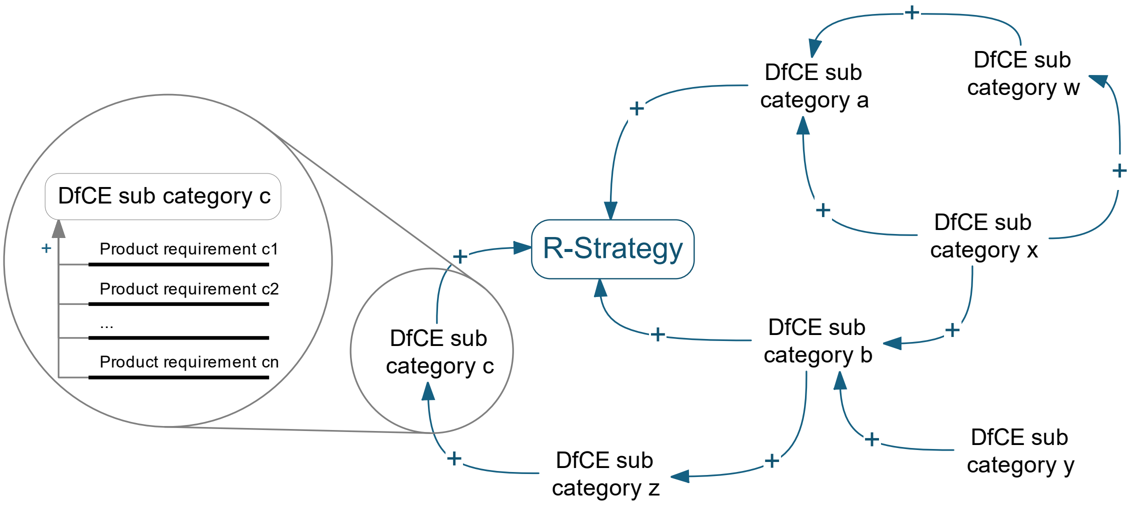

Figure 1. Schematic topology of R-strategies' causal loops to design for circularity sub-categories and their related product requirements.

circularity (Shahbazi & Jönbrink, 2020). By clarifying the relationship between R-strategies and product requirements, this review seeks to support more effective implementations of the circular economy. The ultimate goal is to derive a consistent set of DfCE guidelines and gain a deeper understanding of the interconnections among related sub-categories.

Methods

A systematic literature review following PRISMA guidelines was conducted using a comprehensive search string incorporating synonyms of circular economy-related terms (e.g., R-strategies, circularity), design (e.g. product) and guidelines (e.g., strategy, concept, framework, tool). The search yielded a total of 767 articles published between 2018 and 2023, sourced through Fraunhofer eLib, which simultaneously searches over 250 databases, including Web of Science, Scopus, SpringerLink, and Elsevier ScienceDirect. Additional 59 articles were identified through snowballing. After removing duplicates and irrelevant articles following exclusion criteria, 77 were included in the review.

Relevant literature was coded using an inductive system (Kuckartz & Rädiker, 2023) following source terminology. This approach facilitated the identification of relevant sub-categories of DfCE. Then network mapping was conducted to visualize the interdependencies between different sub-categories of DfCE guidelines and their connections to the various R-strategies. To enhance clarity, redundancies were identified, and sub-categories closely related in content were merged and renamed during a workshop with experts. Given the different R-concepts used in the articles, the 10R framework by Potting et al. (2017) was uniformly applied to all sub-categories, resulting in adjustments to the network connections. Each guideline was reviewed for suitability and reassigned to the appropriate sub-categories if necessary.

Results

Initially, 63 sub-categories were identified from the literature. Following restructuring and standardization, 45 sub-categories of DfCE guidelines were established, encompassing all ten R-strategies. Over 1000 separate product requirements aimed at instructing developers and designers on creating more circular products were retrieved and condensed into approximately 600 final requirements.

To illustrate the differences between R-strategies regarding their relevant sub-categories, specific strategies and their associated guidelines were examined. For example, *remanufacturing* is predominantly supported by sub-categories such as accessibility, aesthetics, cleanability, compliance, disassembly, documentation, physical durability, inspection, interchangeability, logistics, longevity, reassembly, recyclability, and update capability (Babbitt et al., 2021; Shahbazi, 2023; Zhang et al., 2019). In contrast, the *reduce* strategy is mainly affected by sub-categories such as waste elimination, simplification, efficiency, longevity, physical and emotional durability, user participation, and dematerialization (Acaroglu, 2020; Aguiar & Jugend, 2022; Alivojvodic et al., 2020; Babbitt et al., 2021; Hollander, 2018). This demonstrates that these R-strategies are associated with distinct sets of product requirements and design considerations, highlighting significant differences in how each strategy influences product development to enhance circularity effectively.

Discussion

The distinct emphases observed across different R-strategies highlight the nuanced ways in which they influence product requirements. Narrowing strategies, excluding Refuse, place greater importance on organizational considerations, suggesting that internal processes and systems are critical for enhancing circularity through these strategies. Slowing strategies focus on product architecture, emphasizing design features that extend product lifespans, such as ease of repair and upgradeability. Closing strategies focus on materials, highlighting the crucial role of material selection and recyclability in achieving a closed-loop system. Refuse stands out due to its unique focus on material and functionality and its relatively limited number of categories. These findings indicate that each R-strategy may necessitate specific design considerations aimed at addressing particular aspects of product development to proactively enhance circularity. Understanding these nuances allows for a more targeted application of DfCE guidelines, enabling designers and developers to prioritize attributes that align with the desired R-strategy.

Conclusions

By synthesizing and standardizing guidelines from the literature to a common framework, the study offers a structured approach to integrating circularity into product design. These insights assist designers and developers in aligning products with specific R-strategies, ultimately enhancing the effectiveness of circular economy implementations. As not every product solely incorporates features that can be assigned to a distinct product or material group but rather are a combination of such, it is important to build future specific guidelines on a common framework to allow for combination and transfer. This research establishes the groundwork for such standardization. Future work should focus on creating standardized metrics for assessing adherence to R-strategies at the product requirement level, as suggested by Aguiar et al. (2017), enabling easy assessment and documentation of relevant actions. Additional studies could examine the practical application of these guidelines in industry, providing empirical data to refine DfCE strategies.

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