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Towards design for cross-generational remanufacturing: guidelines to enable a forward-looking circularity

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ABSTRACT: To enable a circular economy, remanufacturing is considered a key strategy due to the high level of value retention. However, for short-cycled products, the accelerated obsolescence of conventionally remanufactured products on the secondary market poses challenges to leverage the potential. Cross-Generational Remanufacturing (CG-Reman) has been developed as a new concept in response, which aims to restore used products into the latest generation for sale on the primary market. For its practical success, it is critical to support product engineers in designing products suitably. Hence, in this paper we further explore the overall CG-Reman process with a lifecycle description, derive requirements for the product's design and conduct a systematic literature review of 209 sources targeting selection, clustering and matching of Design-for-X (DfX) guidelines with the needs for CG-Reman.

KEYWORDS: sustainability, design for x (DfX), circular economy, cross-generational, integrated product development

1. Introduction

One of the critical challenges of our era is achieving sustainable growth amidst resource scarcity (United Nations, 2024). In response, the circular economy (CE) aims to reduce energy and resource consumption by fostering circular resource flows through value-retention strategies like reuse, remanufacturing, and recycling. (Ellen MacArthur Foundation, 2013). While conventional remanufacturing holds great potential due to the sustained integrity of product subsystems instead of circulating on material level (Kurilova-Palisaitiene et al., 2023), practical challenges arise from secondary market dynamics, cannibalization and limited customer acceptance (Arnold et al., 2021) resulting in a adoption rate below its potential (Parker et al., 2015). To address these challenges, the concept of Cross-Generational Remanufacturing (CG-Reman) has been defined as *"planned and anticipated industrial process of restoring a used product/system from an older generation to a product/system of the latest generation with original as-new condition and performance [which is] offered on the primary market [. . .]"* (Tusch et al., 2024, p. 6). Our previous work has focused on selecting suitable product categories and identifying the most promising product subsystems (Tusch et al., 2025). This paper seeks to expand on the concept through a lifecycle description, derived requirements, and a foundation for methodological support in designing products and systems fit for CG-Reman. The latter is approached via a systematic review of Design-for-X (DfX) guidelines, which we selected and assessed for their suitability as design support for CG-Reman. DfX was selected for its ability to target specific engineering goals early in product development and its applicability and relevance in industrial practice (Meerkamm et al., 2018). The paper is organized as follows: Section 2 outlines the research background on (CG-)Remanufacturing and Design-for-X. Section 3 details the research approach. Section 4 presents the results, including a generic

CG-Reman lifecycle, derived requirements, and exemplary guidelines. Finally, Section 5 summarizes and discusses the contributions while offering suggestions for future research.

2. Research background

2.1. From remanufacturing to cross-generational remanufacturing

As stated in the introduction, an especially promising R-strategy within the context of CE is given by remanufacturing (hereafter "conventional remanufacturing"), which has potential to retain product value by enabling components to undergo multiple full usage cycles and can outperform other circular strategies (Kurilova-Palisaitiene et al., 2023; Tolio et al., 2017). In conventional remanufacturing, used products ("cores") are processed through several phases, which typically consist of disassembly, cleaning, inspection, restoring, reassembly and testing (Ijomah et al., 2007a; Kauffman & Lee, 2013; Steinhilper, 1998). These steps may vary depending on the specific industry or company (Butzer & Schoetz, 2016). However, conventional remanufacturing is limited by challenges such as product obsolescence, a lack of technological adaptability, and evolving customer requirements (Aziz et al., 2016). The concept of Cross-Generational Remanufacturing (CG-Reman) was developed as one response to these challenges and describes a new strategy that aims to maximize the value retention from conventional remanufacturing by integrating used subsystems into new products for the primary market. This is addressed through a planned and anticipatory process that involves adapting and remanufacturing subsystems to meet the specifications of the latest product generation. The key idea is to provide full customer value without the risk of cannibalization and reduced resource utilization (Tusch et al., 2024). However, as of today it is crucial to address the operationalization gap of the concept. Hence, the development of design support for practitioners is required.

2.2. Design-for-X (DfX) and DfX frameworks

To address the complexity originating from multiple and often conflicting targets in product engineering, the idea of Design-for-X (DfX) has been established (Kuo et al., 2001) based on the success of the early concepts of Design for Assembly (Boothroyd & Dewhurst, 1983) and Design for Manufacture (Stoll, 1988). Today, Design-for-X is an umbrella term encompassing a wide range of design principles and methods aimed at helping designers optimize specific aspects of the product lifecycle (Ijomah et al., 2007b; Mesa, 2023). Design-for-X approaches can be clustered along two dimensions: first, by the "X" they aim to optimize for, and second, by the nature of support offered. The "X" can represent either a specific phase of the product lifecycle, such as manufacturing or assembly (van Doorsselaer & Koopmans, 2021), or a desired product attribute ("virtue"), such as safety, quality, or cost (Meerkamm et al., 2018). The latter is sometimes referred to as Design-to-X (VDI, 2018). On the other hand, the nature of DfX support (often referred to as "tools", cf. Arnette et al., 2014) is subject to great variety, which can be explained by e.g. the lack of consistent standards for DfX (Becker & Wits, 2013). While other forms are existing, most approaches are found on guideline level. However, the application of individual DfX is often challenging, due to the large number of potential solutions (Arnette et al., 2014; Kuo et al., 2001) as well as often conflicting interdependencies (Lindemann, 2007). One way to address some of the challenges is by combining multiple DfX either on concept or guideline level, which is essential for achieving optimal design solutions and sometimes referred to as "DfX frameworks (Arnette et al., 2014).

DfX has become the most relevant basis for qualitative tools in eco-design (van Doorsselaer & Koopmans, 2021). Consequently, within the context of circularity and conventional remanufacturing, various examples of DfX frameworks can be found in literature: Arnette et al. (2014) developed an integrated framework for Design for Sustainability, hierarchically organizing prominent DfX methods based on their interdependencies and aligning them with the three dimensions of sustainability: ecological, economic, and social equity. Charter and Gray (2008) introduced a Design for Multiple Lifecycles framework by combining various DfX methods, including Design for Cleaning, Product Reliability, Durability, and Remediation. Go et al. (2015) developed a Design for Multiple Lifecycle (MLC) framework by integrating guidelines from different lifecycle stages, such as Design for the Lifecycle, Design for the Environment, Recycling, Reuse, Remanufacturing, Disassembly, Assembly, Maintainability, Upgradability, and End-of-Life. Yang et al. (2015) proposed a Design for Remanufacturing framework by combining guidelines for Reverse Logistics, Disassembly, Sorting and Inspection, Cleaning, Reconditioning, Reassembly, and Testing. Hilton (2021) developed a similar

Design for Remanufacturing framework by clustering guidelines into newly formed DfX categories, such as Design for Integrated Value, Design for Viability, and Design for Active Prevention. Similarly, Pozo Arcos et al. (2018) established a Design for Circular Economy framework by integrating guidelines for Cleaning, Diagnosis, Disassembly, Reassembly, and Storage. While these existing frameworks at the guideline level are promising – and we adopted a similar approach by combining guidelines from selected DfX methods – they lack a specific cross-generational focus, which this study seeks to address.

3. Research objective and approach

With this paper, we aim to both further elaborate the previously proposed concept of CG-Reman and lay a foundation for engineering support to design suitable products and subsystems in the form of an initial list of DfX guidelines for CG-Reman, i.e. DfCG-Reman guidelines. To do so, it is necessary to take a lifecycle perspective, in line with existing similar research efforts (e.g., Arnette et al., 2014; Go et al., 2015). Based on a detailed analysis of the CG-Reman lifecycle we plan to derive requirements for CG-Reman-suitable products, which are then matched with existing DfX guidelines coming from a systematic literature review, cf. Figure 1

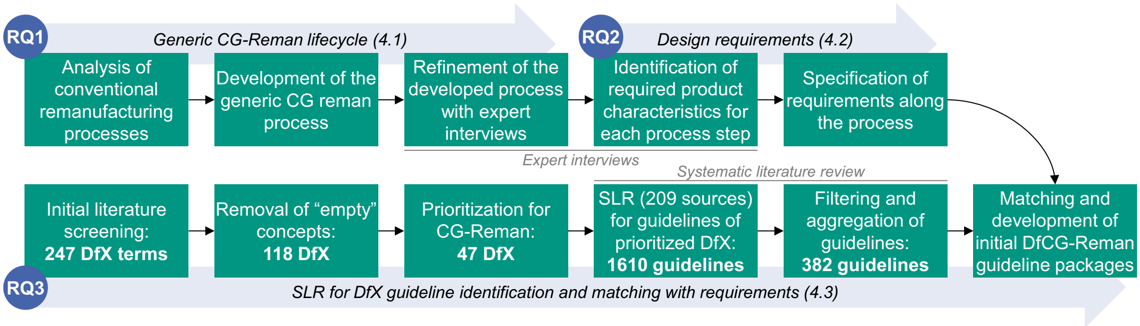

Figure 1. Research approach applied in this paper

This was methodologically guided by three research questions (RQs). First, since the CG-Reman lifecycle has not been described yet, a more thorough process description is addressed in our first RQ:

> *RQ1: How can a generic lifecycle process for CG-Reman be described to facilitate the derivation of design requirements?*

To derive a process description, we identified 7 processes for linear phases and 10 remanufacturing process chains from literature, which we used as starting points to merge them to an end-to-end CG-Reman lifecycle process. From a detailed analysis of the identified process steps, we then needed to derive requirements for CG-Reman suitable (sub-)systems, leading to our second RQ:

> *RQ2: Which requirements for product design can be derived from the CG-Reman lifecycle?*

This question was approached by conducting interviews with conventional remanufacturing experts from industry and academia in addition to an explorative literature search and analysis. Lastly, we needed to identify relevant DfX guidelines that might address the identified requirements. For this, we conducted a systematic literature review of the current DfX landscape guided by our third RQ:

> *RQ3: Which DfX guidelines currently exist and can support the design for CG-Reman?*

As mentioned in chapter 2.2, the DfX research landscape in general is extensive, and in some cases provides only vague concepts with little or no depth at all. From 247 initially identified DfX terms gathered from review papers and standard reference works, only 118 yielded at least one actual publication containing the respective DfX name in its title using a script-based Scopus search (cf. Figure 1. From the terms with results, we subsequently did a first prioritization to identify 28 potentially relevant DfX (frameworks), such as Design for MLC, and eliminate those with an "X" of no relevance for CG-Reman (e.g., Design for 4D printing). Still, we also included 19 concepts that did not have initial results but seemed potentially relevant into a subsequent detailed combined systematic and explorative literature review. From screening 209 sources, we identified 51 sources that contained a total of 1610 individual guidelines. In a last step, we filtered this longlist for duplicates and relevance, added keywords and aggregated guidelines with similar content where applicable, leaving a remainder of 382 guidelines. These were then used to find matches for the identified requirements in RQ2.

4. Results

4.1. Generic cross-generational remanufacturing lifecycle

Based on a literature review of existing lifecycle descriptions for conventional remanufacturing, 10 sources could be identified and were analysed for their specific differences and common ground (ANSI, 2016; Bras, 2014; Butzer & Schoetz, 2016; DIN, 2023; Go et al., 2015; Ijomah et al., 2007b; IRP, 2018; Kauffman & Lee, 2013; Parkinson & Thompson, 2003; Steinhilper, 1998). While most of these processes are relatively abstract in their description level, the intention here was to sketch a process with a sufficient level of detail to identify potential opportunities and pitfalls for product design. Hence, a lifecycle view of CG-Reman with five linear phases and seven (CG-)Reman phases was developed and selectively detailed where appropriate, cf. Figure 2. This was further refined by interviews with remanufacturing experts from industry. The key element for the CG-Reman process chain is the leap across generations (depicted by the two shaded rectangles), which is required for the forward-looking approach to circularity. The difference to conventional remanufacturing can also be seen visually in the figure, where a loop would be closed within the original (old) product generation. The process can be and should be targeted to be extended with more generational leaps (in theory indefinitely), albeit the complexity of the process and share of value retention will likely reduce correspondingly.

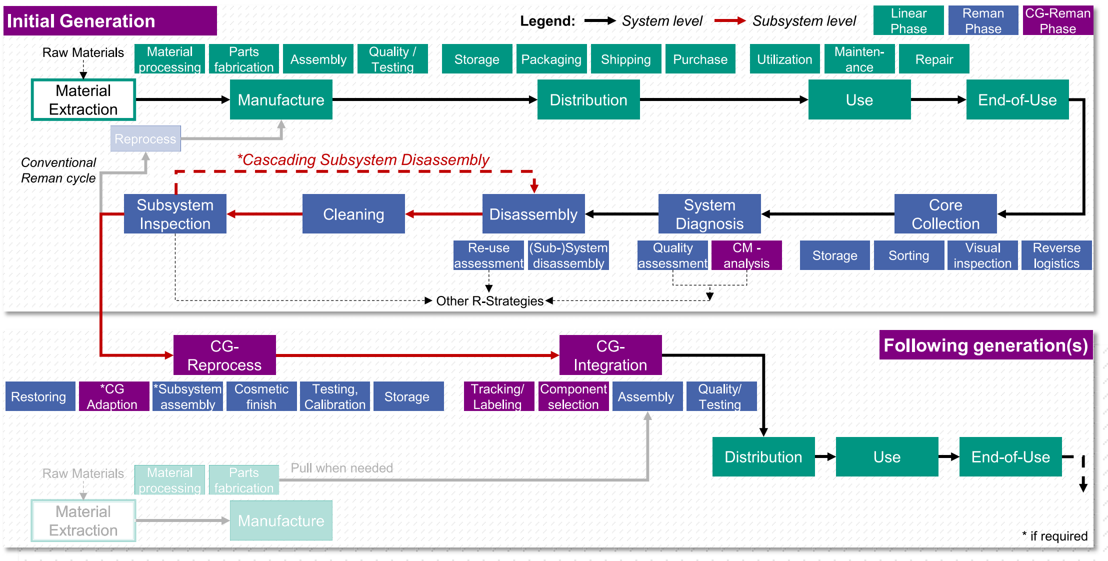

Figure 2. Overview of generic cross-generational remanufacturing lifecycle

The CG-Reman process consists of linear phases *Material Extraction*, *Manufacture*, *Distribution*, *Use* and *End-of-Use* (in this case not End-of-Life) in green, and the remanufacturing phases *Core Collection*, initial *System Diagnosis*, *Disassembly*, *Cleaning* and *Subsystem Inspection* in blue, which was synthesized from the literature quoted above. The process continues with the *CG-Reprocessing* phase, which crucially includes the *CG-Adaption* step (CG-phases in purple). Here, if required, the respective subsystem is altered to ensure compatibility for the new product generation after or while being functionally *restored*. Ideally, this stage can be omitted by an entirely communal subsystem design, however in reality, some functions, interfaces or joining mechanisms might require (planned) adaptions. Lastly, in the *CG-Integration* phase the restored and adapted subsystems are integrated with the linear assembly of primary market products. The pull-process of linear production complementing the circular process cannot be avoided due to two main reasons: First, for subsystems with no CG-Reman potential (planned change), and second, for subsystems where circular supply is smaller than the market demand of the new product. Even with constant market demand, some returned subsystems in bad condition (e.g., when the residual core value is smaller than the effort for restoration) will be aborted during the

process and need to be processed through other R-strategies (e.g., Recycling). Due to the in-line integration of circular and linear production, it becomes obvious that the process is only feasible for the original manufacturer of the product and not for third-party entities. After finishing the assembly and respective final testing, products will experience another usage cycle in the new product generation.
Along the process the product is kept in its integrity until the *Disassembly* stage, before then being continued on subsystem level (red arrows). The disassembly needs to be conducted in cascading fashion, i.e. it should always be tried to salvage the entire subsystem before deciding to further disassemble. The re-assembly to a product of the new generation is part of the *CG-Integration* phase. Here, components that belonged to the same product in the old generation are not (necessarily) part of the same product in the new generation. Tracking the individual history of these instance-specific products is crucial, as subsystems with varying usage cycles must still meet primary market quality standards.
To the authors' belief, this process requires anticipation and CG planning during the initial generation's development, including deliberate selection of subsystems for CG-Reman (and potential exclusion, e.g. due to critical new functions of future product generations) as well as tracing and mitigating potentially conflicting future variations to these subsystems. Hence, the entirety of challenges that may arise during this extended lifecycle already needs to be considered in product engineering.

4.2. Requirements for cross-generational remanufacturing

The realization from Chapter 4.1 asked for specific requirements that need to be fulfilled during product engineering. To derive these, the lifecycle description was analysed step by step for resulting requirements for the product's design. This meant, that general characteristics (e.g., "needs to be disassembled") rather than optimization thereof (e.g., "efficient disassembly process") were targeted. This process was supported by interviews with remanufacturing experts from the automotive industry (4 in-depth interviews) and academia (11 phase-specific interviews). Table 1 shows all identified requirements with their relevant lifecycle phases in chronological lifecycle order. Existing literature that stated similar requirements or notions for conventional remanufacturing were checked to ensure relevance and are added for reference, where applicable. We deliberately considered the entire process, even though a major part of the derived requirements (A-J) unsurprisingly has strong intersections with conventional remanufacturing. However, for the cross-generational case, the challenge is not only more

Table 1. Overview of derived CG-Reman requirements in chronological lifecycle order.

#	Derived requirement (relevant phase)	Similar notions from literature
A	Subsystems and components to be CG-Remanufactured must be able to withstand multiple use phases (Use)	*Hatcher et al., 2011; Prendeville et al., 2016*
B	A mechanism for retrieving used products from consumers to OEMs must be established (EoU)	*Aziz et al., 2016; Ijomah et al., 2007a; Kauffman & Lee, 2013*
C	The initial system condition of the used product must be identifiable. (System Diagnosis)	*Sundin & Bras, 2005; Expert Interviews*
D	The product must enable disassembly for the retrieval of CG-remanufacturable subsystems (Disassembly: System Disassembly)	*Hatcher et al., 2011; Ijomah et al., 2007a; Kauffman & Lee, 2013; Prendeville et al., 2016; Sundin & Bras, 2005*
E	The joining mechanisms of subsystems and components for CG-Reman must withstand multiple disassembly phases (Disassembly)	*Expert Interviews*
F	Subsystems and components not CG-remanufacturable must be suitable for other R-Strategies (Disassembly: Re-use Assessment)	*Fofou et al., 2021*
G	The product and its subsystems and components must be able to be cleaned in multiple CG-Reman processes (Cleaning)	*Sundin & Bras, 2005*
H	The product must allow disassembly to the appropriate degree to maximize the retrieval share (Cascading subsystem disassembly)	*Schmitt et al., 2023*
I	Subsystems and components must allow identification of their functional condition for onward use (Subsystem Inspection)	*Expert Interviews*
J	Subsystems and components must allow restoration of their required functional specification (CG-Reprocess: Restoring)	*Ijomah et al., 2007a; Kauffman & Lee, 2013*
K	Subsystems and components must allow adaption or re-use for integration into a new product of following product generations (CG-Reprocess: CG-Adaption)	*Expert interviews*
L	Subsystems and components must allow identification of their history and status to enable their integration into linear production (CG-Integration: Tracking/Labelling, Component Selection)	*Expert interviews*
M	The product must be designed for integration into the respective latest-generation production system (CG-Integration: Assembly)	*Fegade et al., 2015*

complex through new requirements (K-M), but also the fulfilment of the conventional remanufacturing requirements becomes more complicated with potentially new guidelines to address these challenges. As an example, from the step of a potentially necessary *CG-Adaption* within *CG-Reprocess* phase, the requirement K can be derived. This is necessary, because in addition to pure functional restoration, the cross-generational approach requires either equal design of the respective subsystems in the two generations or the consideration of a possible adaption, which could also involve additional machining. Adjacent notions from the field of upgrading were used to refine the requirement (e.g., Xing et al., 2007), even though coming from a different focus. While these requirements were deliberately kept solution-agnostic, they were used as an orientation for the subsequent DfX-guideline literature review.

4.3. DfX guidelines for cross-generational remanufacturing

Based on the identified requirements, existing DfX guidelines that might be able to support these were sought. With the systematic literature review described in Chapter 3, a condensed list of 382 aggregated guidelines could be derived. These guidelines were then manually matched to keywords as well as the respective process phases and the defined requirements A-M (cf. Chapter 4.2), resulting in 12 guideline packages. These were structured hierarchically, i.e. guidelines that would support or detail another guideline in the package were subordinated. Given the amount of guideline packages and guidelines, only excerpts of two examples of guideline packages A (addressing robustness) and K (existing guidelines addressing the need for cross-generational compatibility or adaption) can be presented here (truncations indicated by "... "). The full set of guidelines can be obtained from the authors upon request.
As can be seen by the requirements and their corresponding process phases, most of the packages focus on steps also present in conventional remanufacturing and can hence be addressed by existing Design for Remanufacturing. Guideline package A is an example of such element, as robustness during the customer use phase is a common consideration also within existing Design for Remanufacturing frameworks. The guideline package synthesized from literature can be found in Table 2, while it combines both engineering design measures (A1) and influencing customer behavior (A2).

Table 2. (Aggregated) DfX guidelines from literature to address requirement A (Use).

#	Guideline	Reference source(s)
A1	More robust design	*Go et al., 2015; Kutz, 2007*
A1.1	Make sure core components including their joints are robust enough to be reused repeatedly	*Go et al., 2015; Shahbazi & Jönbrink, 2020; Vezzoli, 2018*
	...	
A1.2	Overdesign core components to maximize usage cycles	*Mesa, 2023; van den Berg & Bakker, 2015; Yang et al., 2015*
A1.2.1	Oversize components related to stress, geometry, available space, power and energy	*Bischof & Blessing, 2008*
A1.2.2	Incorporate multiple life cycle part variation into tolerance allocation to allow core reuse with minimum dimension restoration required	*Hilton, 2021*
	...	
A1.3	Minimize the amount of parts requiring frequent repair or replacement	*Ijomah et al., 2007a*
A1.3.1	Reduce number of parts subject to wear	*Kutz, 2007; van den Berg & Bakker, 2015*
	...	
A1.4	Provide readable labels, text, and barcodes that do not wear off during the products service life and position them at visible locations	*Go et al., 2015; Kutz, 2007; Yang et al., 2015*
A1.5	Select strong, robust materials that resist stress, wear, corrosion, discoloring, and degradation, ensuring they maintain their integrity through multiple lifecycles	*Go et al., 2015; Hilton, 2021; Ijomah et al., 2007a; Mesa, 2023; Shahbazi & Jönbrink, 2020; van den Berg & Bakker, 2015*
	...	
A2	Emotionally connect the customer with the product to assure the product endures	*Hilton, 2021*
	...	

More specific for the case of CG-Reman is guideline package K, which addresses the challenge of ensuring a planned compatibility or adaption possibility, cf. Table 3. This can be achieved either through reusing (focused by guidelines K1, K4) or adaption (K2, K3). Here, most guidelines that could be matched originate from the field of upgrading, which is conceptually different. While upgrading primarily addresses the subsystems that change across generations, here subsystems that remain constant but are still removed from the previous product integrity are addressed. Still, some of the guidelines provide valuable direction for product engineers to address the challenge.

Table 3. (Aggregated) DfX guidelines from literature to address requirement K (CG-Adaption).

#	Guideline	Reference source(s)
K1	Design a durable, robust platform with standardized, well-defined interfaces that remain fixed across product generations and allow for easy upgrades and the separation of components that are likely to change (modules)	*(Boer & Boer, 2019; Hashemian, 2005; Kutz, 2007; Shahbazi & Jönbrink, 2020; Yang et al., 2015)*
K1.1	Make changes to key components without redesigning others	*(Boer & Boer, 2019)*
K1.2	Divide the products into modules, and place all parts that need to be upgraded into one module	*(Hilton, 2021; Shahbazi & Jönbrink, 2020; van Doorsselaer & Koopmans, 2021)*
	...	
K2	Enable adaption of components to meet the requirements of the new product generation	*Expert Interview*
K2.1	Design products with add-on modules that can accommodate future upgrades, personalization, and evolving functionalities. These modules should be separate from core functions and customizable to meet specific requirements, enabling multiple functions within a single adaptable product	*(Bischof & Blessing, 2008; Hashemian, 2005; Mesa, 2023; van den Berg & Bakker, 2015)*
K2.2	Provide extra features and functionalities in a design for possible future needs.	*(Hashemian, 2005)*
	...	
K3	Make it easy to upgrade the product	*(Ijomah et al., 2007a; Shahbazi & Jönbrink, 2020; van den Berg & Bakker, 2015)*
	...	
K3.3	Think about the (possibly adverse) dependencies and effect of the upgrade on other product components	*(Shahbazi & Jönbrink, 2020)*
	...	
K4	Make sure the components and parts are back and forward compatible	*(van den Berg & Bakker, 2015)*
K4.1	Make sure that components are required across models and products, e.g. like the same type and size of screws, are exchangeable and can be reused	*(Shahbazi & Jönbrink, 2020)*
K4.2	Rely on consistent and repeatable design solutions	*Expert Interview*
K4.3	Reuse components in multiple products and generations	*(Boer & Boer, 2019; Hilton, 2021)*

While the approach to the identification of suitable guidelines was directed by a lifecycle-based requirements view, their application by product engineers demands a design-oriented perspective. When comparing the identified guidelines, different abstraction levels could be identified and were assigned: system-level guidelines (e.g., modularity) apply across the entire product and all subsystems, whereas subsystem/component-level guidelines (e.g., material requirements, internal disassembly) are specific to individual subsystems. In the core guideline packages shown above these abstraction levels are still mixed. However, given that in CG-Reman not all subsystems are maintained at a high value retention level but some are predesignated for alternative R-strategies (cf. Chapter 4.2), not all guidelines are relevant for all subsystems. Ways to identify subsystems with high CG-Reman potential were presented previously (Tusch et al. 2025). Hence, we can split the scope of application of the identified guidelines based on the specific subsystem considered, cf. Figure 3.

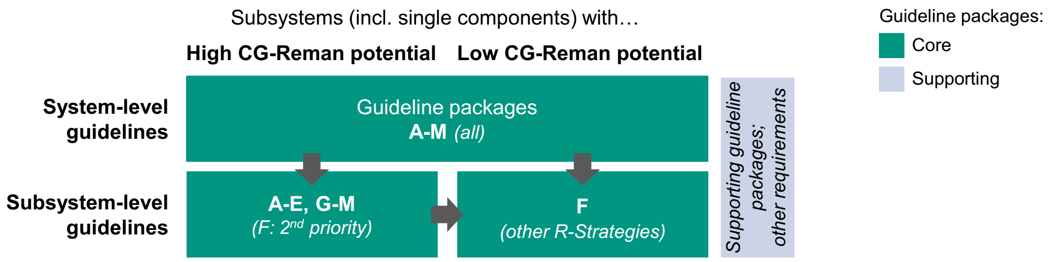

Figure 3. Scope of application of the developed DfCG-Reman guideline packages

Additionally, supporting guideline packages that enhance the process but are not essential for CG-Reman (e.g., facilitating automated disassembly), were established. General requirements, that might be important for a successful product, such as optimization for efficient linear manufacturing and assembly as well as cost-efficiency further will contribute to a holistic approach and should be closely aligned.

5. Summary, discussion and outlook

This study explores Cross-Generational Remanufacturing, introducing a generic lifecycle (RQ1), high-level design requirements (RQ2), and initial DfCG-Reman guidelines synthesized from existing literature (RQ3). These contributions have been previously unexamined in the literature. Additionally, the proposed CG-Reman lifecycle offers a synthesized and more detailed process depiction of conventional remanufacturing steps, validated by industry experts. Our study moreover confirms prior findings (e.g., Arnette et al., 2014) highlighting the lack of transparency in DfX approaches due to varying interpretations, inconsistent structures, and limited conceptual depth. In general, many of the circularity guidelines remain broad and repetitive, offering little specific advice for design.

The initial DfX guideline packages outlined in this study serve as a foundation for further development, particularly in refining specific guidelines for CG compatibility. However, they only represent an initial step towards a consistent DfX framework, as practical applicability (e.g, through case studies) has not yet been tested and language adjustments for clarity and coherence remain unaddressed. They also do not yet support upstream strategic decisions such as usage cycle lengths and generation time in market that might impact overall success or suitability of CG-Reman for a given product or company. To mitigate the inherent challenges of DfX frameworks, such as potential contradictions between individual DfX, this study established its initial framework at the guideline level, aiming to resolve direct conflicts within selected guideline packages. However, on the macro level (i.e., between guideline packages), this challenge from different and potentially conflicting requirements is still to be addressed. Hence, while providing a solid foundation for further methodological development, relying solely on existing DfX guidelines is likely inadequate. Instead, an integrated and holistic approach is needed, incorporating prioritization mechanisms like scoring, weighting, and relationship charts from the guideline level to aggregated decision-making. An example for such higher-level trade-off would be balancing the potential loss of recyclability at a subsystems' EoL in favor of enhanced suitability for CG-Reman, i.e. on higher value retention levels. Given the complexity and both intra- and cross-generational interdependencies, a model-based engineering approach appears promising. These challenges will be further tackled as part of the CRC 1574 funded by the German Research Foundation (DFG), to further advance the design of forward-looking and cross-generational circular products.

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