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Towards Design for Cross-Generational Remanufacturing: A Literature Review and Concept Proposal

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Abstract: This paper proposes the concept of cross-generational (CG) remanufacturing, integrating remanufactured components into new products for the primary market to overcome trade-offs between new-product cannibalization, pricing, and customer acceptance. Employing a CG perspective can reduce costs and increase profits for manufacturers, and appeal to end-customers seeking environmentally responsible choices. Aiming for an explicit nomenclature, the study suggests a definition for CG-Remanufacturing and a classification for products that are especially suitable based on literature review and analysis.

Keywords: Sustainable Design, Circular Economy, Design for X (DFX), Remanufacturing, Product Development

1 Introduction & Motivation

A key challenge of our time is the sustainable growth under the constraints of resource scarcity (United Nations, 2019). The concept of circular economy (CE) has been developed to reduce both the consumption of energy and primary resources. The key idea is a circular resource flow on distinct value creation tiers (also called R-strategies), such as maintain, reuse, remanufacture and recycle (Ellen MacArthur Foundation, 2013). In practice, it has become common to produce products with recycled materials, which is sometimes even used as a differentiator when addressing customers (Polyportis et al., 2022). While remanufacturing has found initial footholds in certain sectors, its adoption rates remain comparatively low due to a variety of key challenges (Arnold et al., 2021). Among these are issues related to reverse logistics, labor-intensive processes, and limited customer acceptance of secondary market products (Arnold et al., 2021). For short-cycled products, the latter can also be structurally driven by a limited overlap of returned products (cores) with demand for the old product generation (Östlin et al., 2009). As a result, remanufacturing today is often only executed ex post and not sufficiently considered during product engineering (Tolio et al., 2017). Given the higher value preservation of remanufacturing and its significant potential for enhancing resource efficiency and energy savings (Sutherland et al., 2008), it is imperative to find ways to leverage remanufacturing for more customer-attractive products.

The idea of cross-generational (CG) thinking, i.e. extending over several product or system generations, is of utmost concern in the model of SGE – Systems Generation Engineering by Albers and Rapp (2022) and its related research fields. Given that this view facilitates a holistic view of product engineering beyond a single product in development, which seems suitable for planned and forward-looking sustainability, we want to link this idea to the challenges of developing circular products and systems. Hence, in this contribution, we strive to apply this CG thinking to the conventional (intra-generational) approach of remanufacturing. To do so, we suggest the concept of cross-generational remanufacturing, an approach that inherently plans and designs for remanufacturing into new products for the primary market. This is especially important to escape the frequent and well-researched trade-off between new-product cannibalization, pricing, and customer acceptance typically associated with remanufacturing from the manufacturer's perspective (e.g., Zhou et al., 2017). Additionally, there are opportunities to realize economies of scale and reduce capital investment when integrating circular and linear production, while customers could buy the latest products with an environmentally responsible choice. Since it is evident that designing products for such an approach will create more complexity, we aim to lay a foundation for further research endeavors by providing a clear and explicit nomenclature for a common understanding. Hence, within the scope of this contribution, we first explore the current body of literature for related concepts or insights through a literature review based on screening and analyzing a total of 169 sources (37 full text). Building on that, we derive a definition and explore the characteristics of a CG perspective. Lastly, we propose an initial classification to identify products that could be suitable for a "Design for Cross-Generational Remanufacturing".

2 Research Background

2.1 Remanufacturing

Circular Economy describes a concept of an "an industrial system that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013). As a key strategy to achieve this, remanufacturing is commonly defined following the definition by Ijomah et al. (2004) as "the process of returning a used product to at least OEM original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent". Remanufacturing holds potential to conserve resources and reduce energy consumption by up to 85% through reusing up to 90% of previously produced components in recreating a functioning product (Kim et al., 2009; Sutherland et al., 2008; Tolio et al., 2017) and therefore outperforms other circular strategies for technological products (Kurilova-Palisaitiene et al., 2023). This also translates into cost savings and additional revenue potential for manufacturers, especially in industries with strong secondary markets (Kumar and Ramachandran, 2016). However, application of remanufacturing is currently mostly limited to special cases, such as spare parts recovery and secondary market products (Charter and Gray, 2008; Corum, 2022; Seitz, 2007). The reason for this limited adoption is a variety of key challenges: These include appropriate design for remanufacturing (Golinska-Dawson and Kübler, 2018), market related difficulties such as fear of product cannibalization (Arnold et al., 2021), lack of customer acceptance (Karvonen et al., 2017) and logistical difficulties in ensuring a reverse product flow from customers to manufacturers of products in defined quality (Nasr, 2019; Östlin, 2008). For further challenges and a detailed description of the characteristics we refer to an overview provided by Arnold et al. (2021). It has also been pointed out that the single product view on remanufacturing does not embrace the systems thinking approach of circular economy resulting in unexplored potential from the product design perspective (van den Berg and Bakker, 2015). For the context of this paper, remanufacturing activities that are focused on restoring a product to the same (old) product generation that it has been before will be referred to as "conventional remanufacturing".

2.2 Product Lifecycle and Model of SGE – System Generation Engineering

The term product lifecycle has been used widely in research, while at least two different views are presented (Östlin et al., 2009). While a more market-oriented view considers introduction, growth, maturity and decline (Sundin and Bras, 2005), the concept used in sustainability research is typically related to physical stages from the first idea in product planning, manufacturing and usage until ending in the end-of-life (EoL) treatment of a product (Bender and Gericke, 2021). In this paper, we use the second lifecycle view and refer to the first as demand distribution or product diffusion, as common in remanufacturing literature (Debo et al., 2006). Product engineering describes a part of this lifecycle containing product planning, product development and production system development (Albers and Gausemeier, 2012). While open-loop lifecycles are characterized by product disposal at its end, closed loop lifecycles aim to adopt EoL strategies to minimize environmental impact (Jawahir et al., 2006).

The concept of closed-loop lifecycles can be supported in product engineering through a cross-generational view. Based on this CG thinking, Albers et al. (2015; 2022) have developed the model of SGE – System Generation Engineering to systematically describe product or system engineering in generations. According to this, a product or system generation G_i is a socio-technical system perceived as independent entity in distinction to existing systems, which can be by means of functionality, performance costs or visual characteristics (Albers et al., 2017). For a consistent and time-independent nomenclature, the generation currently in development is labelled $G_{i=n}$, making $G_{i=n-1}$ the generation currently being sold on the market. Product or system generations are exclusively developed through three types of variation from their corresponding reference system R_i containing selected reference system elements (RSE) (Albers et al., 2019): Carryover Variation (CV), with allowed modifications solely to interfaces of the RSE, Attribute Variation (AV), constituted by new development of functional attributes based on an RSE with preservation of the solution principle, and Principle Variation (PV), which describes a change in the solution principle of the RSE to achieve the desired function. The model of SGE considers design reuse in the form of CV in the product engineering space (Albers et al., 2019) but has yet only initially been applied in the context of sustainability and circular strategies (Albers et al., 2024).

3 Research Design

3.1 Research Goal and Research Questions

Based on the potential described in chapter 1, we want to achieve a first step towards the overarching goal of "cross-generational remanufacturing" by defining an explicit nomenclature. To do so, we want to start with potential insights from existing research on the matter. Consequently, we first want to investigate, whether there are currently approaches that deal with remanufacturing components for use across product generations, especially from a product engineering perspective, leading us to our first research question:

> *RQ1: Which current product engineering approaches exist to extend remanufacturing across product generations?*

Building upon the gained understanding, we want to propose a clear definition of the concept of "cross-generational remanufacturing" as well as opportunities and characteristics that we see vital for its operationalization. This leads to our second research question:

> *RQ2: How can cross-generational remanufacturing be characterized and defined, and which products are suitable candidates from a product engineering perspective?*

3.2 Research Approach

Since there are many ways to frame the nomenclature for what we call a cross-generational approach to remanufacturing, we employed a two-way approach consisting of a systematic literature review (SLR) and an explorative search. For the SLR we used the *Scopus* literature database and a search string with a conjunction of four elements: First, we wanted to limit the field to the area of product engineering. Second, we focused on cross-generational approaches. Given different use of these term across schools of thought, we added relevant synonyms. Lastly, we also included adjacent R-Strategies beyond remanufacturing itself to get a broader view. The review considered results from 2017 onwards and in English language. An overview of the final search string can be found in Figure 1. To ensure relevance, results were filtered to the fields of engineering and environmental science.

product development engineering design | product development engineering design **AND** inter* multi* cross* **AND** generation* lifecyc* **AND** reman* refurb* reuse* recond*

Figure 1. Search string used for the systematic literature review

Based on a screening of titles and abstracts a first reduction was performed. The goal here was to quickly dismiss literature with a non-relevant topic or focus, such as construction, knowledge management, (chemical) process technology or deeply specialized use-cases. In a second screening, papers dealing with general sustainability aspects, overarching CE or conventional remanufacturing focus were excluded (cf. chapter 2.1). Furthermore, we added an explorative search leveraging a broader search on Google Scholar and citation-based tools such as Research Rabbit for highly relevant papers. This decision was taken for two reasons: First, some concepts turned out to be linked to the idea but had very distinct nomenclature. Second, performing selective deep dives on specific terms that seemed to be relevant to the topic allowed for testing the level of elaboration. The identified sources were analyzed and discussed regarding the stated research questions. An overview of the approach and the number of sources that remained after each given step can be seen in Figure 2, while one of the sources for full text-review had to be excluded due to no accessibility.

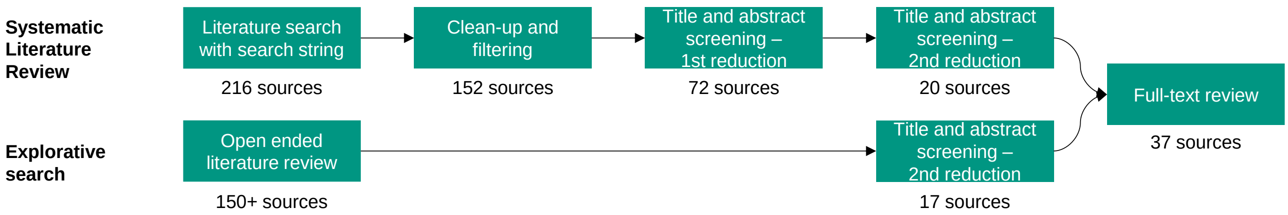

Figure 2. Process of the literature review

For the analysis, we paid special attention to the nature of the approach, potential existing definitions w.r.t. RQ2, attached a category of support (e.g., design guidelines, design optimization, design evaluation/optimization), focus of the work (single product, product families, multiple generations), supporting model theory or methodology and whether an application of the work (industrial/theoretical case study) was presented. We combined these insights from current literature with our proposed approach to characterize its nature, derive a clear definition and identify suitable product characteristics.

4 Critical Review of Approaches to Extend Remanufacturing Across Product Generations

From the small number of relevant results in the literature review and confirmed by authors of relevant papers (Asif et al., 2021; Hapuwatte et al., 2022) it can be seen that the topic is only researched to a very limited extent. When looking into the cross-generational aspect in conjunction with remanufacturing, two types of publications can be distinguished: The majority shows an operations research character, where a modeling approach (e.g., multi-objective optimization) is presented. A smaller part pertains to engineering design in a more direct way, either through methodologies or optimization guidelines. The findings are therefore presented grouped into these two clusters in the following.

4.1 Publications with Operations Research Approach

The publications with operations research approach typically take a sustainability optimization view, e.g., by means of life cycle costing (LCC), life cycle assessment (LCA) or a variant of optimizing for one or multiple of the ecologic, economic, and social aspects of sustainability. We also generally summarize all publications in this cluster that take an optimization problem from a selection of options as basis for their work.

Overall, the specific idea of remanufacturing product across product generations was found to be more explicated in the operations research focused literature. The contribution by Wang et al. (2017) highlights the lack of research and argues for the imperative need of "concurrent design of multiple product generations" (Wang et al., 2017) to address the high likelihood of an overlap of reverse flow of components from one generation with market introduction of the following one. Using a probabilistic model, the authors show that the amount of component reuse can be higher with cross-generational component commonality while highlighting its trade-off with technological component obsolescence.

Kim and Kim (2020) define generational commonality as “a common set of subsystems, modules, and components between different generations of products”. Using a quantitative model and the theoretical case study of a smartphone, the authors show the economic potential of generational commonality on both manufacturing and remanufacturing but competing on separate markets. Their results show significant impact of generational commonality on decreasing cost in both cases and on facilitated EoL collecting due to higher compatibility. However, the tradeoff with limited product differentiation and the risk or lower sales prices is pointed out. The authors highlight themselves that their study only focuses on the number of components that should be shared, and neither analyses which components specifically nor how they should be designed.

Several of the approaches start from product portfolio or product family design to enhance reuse possibilities for remanufacturing, which was already presented by Mangun and Thurston (2002) in initial modeling. In a series of publications presented by a group of researchers around Badurdeen et al. (2018), product configuration design has been used as an approach to identifying optimal component combinations in products, product families and material selection for multi-lifecycle material flow considering multiple sustainability dimensions (Aydin and Badurdeen, 2019; Badurdeen et al., 2018; Bradley et al., 2016). Within the focus of this paper, the extension of these contributions by Hapuwatte et al. (2022) are most relevant: Based on an assessment framework by Hapuwatte and Jawahir (2021), the authors present an multi-objective model to optimize economic and environmental impact. Similar to Wang et al. (2017), the authors incorporate what they refer to as “inter-generational commonality” and integrate a decision-tree logic for component selection in combined remanufacturing and linear manufacturing. Crucially as the only identified prior work with this explicit assumption, the proposed model assumes full equality in specifications (including sales price) between newly manufactured and remanufactured products and at the same time includes potential adverse effects on product utility due to lower differentiation. The authors conclude, that “inter-generational commonality allowed for significant gains in the objective values” (Hapuwatte et al., 2022). Still, the general limitation of the product configuration approach lies in the fact that it can only solve for an optimal combination of given components. It does not guarantee however, that the variants of components to select from are designed in an optimal fashion.

Miyoshi et al. (2022) show the potential of cross-generational compatibility to reduce CO_2 emissions and lifecycle costs of toner bottles significantly. Beyond the applied life cycle market modeling approach, the authors provide initial design suggestions for the specific case of the toner bottle such as increasing durability to increase maximum remanufacturing count, RFID tags to increase collection rate and compatibility between generations. Based on their model, the authors derive an example where increased design and manufacturing spending up to a factor of two for an optimized design can still result in lower lifecycle cost.

Further identified recent contributions in the space include Hossain et al. (2023) and Kang et al. (2023). Both focus on a product configuration approach in product family design with optimal module configurations and component sharing decisions, respectively. The latter work also includes commonality decisions across generations, but again assumes a separated market between new and remanufactured products.

To summarize, there is initial evidence that supports the critical importance and positive impact of component remanufacturing across product generations (Hapuwatte et al., 2022; Miyoshi et al., 2022; Wang et al., 2017) and thus lays a theoretical foundation for the overall objective of our research targets. However, as some of the authors pointed out, this is mostly answering the question of *what needs to be done*, not *how it should be done*. While the operations research perspective can support decision making between given alternatives at a later stage, practical support to proactively design products and subsystems that are optimized for this demand is lacking.

4.2 Publications with Engineering Design Support Approach

While in the operations research cluster initial contributions sharing the specific idea of this paper could be identified, in the engineering design support literature only topically adjacent contributions were found.

The closest approach has been presented by Asif et al. (2021) in the context of circular manufacturing systems. The authors present a methodology to identify modules in products for multi-lifecycle use based on linking strategic disciplines with the concept of product obsolescence types. Their Modular Function Deployment (MFD)-based approach supports the modularization of products along strategic disciplines (product leadership, operational excellence, customer intimacy) and corresponding expected obsolescence type (technological, functional, emotional), which the authors link to the EoL options of upgrading/replacement, reuse, and replacement, respectively. Their industrial case study of a washing machine suggests a second and third life different from the original design but on lower-level market segments.

Go et al. (2015) provide a comprehensive review of different DfX guidelines and evaluate their applicability to multiple life cycle (MLC) processes, which they use as an umbrella term for reuse, remanufacturing, and recycling. They propose an MLC suitability characteristic for products that is being “sold in a market that is tolerant of as-new or second life products” (Go et al., 2015). Though frequently observed, this is somewhat a limitation of the potential since it excludes an attempt to achieve multi-lifecycle products that do not have a negative stigma of a secondary market product.

In the context of multi-lifecycle assessment, Suhariyanto et al. (2017) divide MLC products for assessment in those by design innovation and by technology innovation, while the latter has similarities to what we aim for. The authors pose that in a multi-generation product system only material can be recovered in technology changes. However, even with changing technologies, some subsystems of products are not significantly altered, which would be a missed opportunity stemming from the unclear generation definition used in the paper.

Nag et al. (2022) have conducted an extensive meta-review of current literature reviews in the field of Design for Sustainability and Multi-Lifecycle-Design. They also highlight the need for design and modularization methods for multi-lifecycle design and mention design for standardization (especially between competing companies) as a strategy to enhance flexibility at EoL. While this is most likely only possible through regulatory interception, standardization or commonality across product families and generations is in the control of the manufacturer.

From the regulatory site, the standard IEC 62309 (2004) focused on electrical components already presents the idea of applying used components in products that are brought to the primary market. Belli and Quella (2021) delineate the underlying concept of Qualified-as-Good-as-New (QAGAN, also labelled QUAGAN) from remanufacturing in the fact that “new products” are defined by the above standard in a way that they can contain QAGAN parts. Even though this allows the entry to the primary market with reused or remanufactured components, it is again a reactive way to approach the idea. As a notable concern, the authors also highlight the importance of ensuring potential software compatibility.

While the definition of conventional remanufacturing already includes the possibility of extending the products functionality as compared to its original state when sold for the first time (cf. chapter 2.1, Sundin and Bras, 2005), the topic of upgrade remanufacturing or remanufacturing with upgrade has become a growing concern to address evolving customer requirements (Aziz et al., 2016; Kwak and Kim, 2013). It is different from other upgrading strategies by conducting the upgrade on the manufacturer’s side as part of the remanufacturing process and not in the field. However, it is typically intended to enhance functionality of a product to current market-level rather than addressing emotional obsolescence of a product (Tolio et al., 2017). In this context, Pialot and Millet (2014) emphasize the need for a new design methodology that supports multiple upgrade cycles. Wu et al. (2023) highlight that a distinctive “design for upgrade remanufacturing” (DfURem) is most critical for success, using the example of a lathe. However, given the nature of product upgrades, the authors take a given product within a generation in the market $G_{i=n-1}$ as constraint for a customized methodology and individual upgrading cases. An adjacent approach integrating maintenance and remanufacturing for life extension of capital goods has been presented with “Adaptive Remanufacturing” by Burggräf et al. (2023). However, none of these approaches bears the essence of a fully cross-generational view.

4.3 Summary of the Findings

To answer RQ1, we identified two clusters of publications. While considerable attention has been directed towards intra-generational remanufacturing over the years, cross-generational approaches remain relatively underexplored. The most critical to mention are multi-lifecycle design, upgrade remanufacturing, product family design for remanufacturing, intergenerational commonality and QUAGAN. The critical importance of appropriate product design has been a key concern in most of the identified publications (Asif et al., 2021; Go et al., 2015; Miyoshi et al., 2022). While some previous research has dedicated attention to the multigenerational aspect of products (i.e. acknowledging the fact that products are developed and released in generations) in the context of remanufacturing, this was mostly done with a focus on supply chain (literature on closed-loop supply chains, e.g. Keshavarz-Ghorbani and H. R. Pasandideh (2023)) or market/sales related challenges (e.g., Bayrak et al. (2024)). Still, the identified contributions can serve as a basis to realize the approach envisioned in this paper.

As a general observation, several approaches refer to the concept of “multi-lifecycle”. This is not very clear, since it can be understood to describe conventionally remanufactured or recycled products going through the process multiple times in a cascaded or secondary-market approach or leveraging remanufactured components in a cross-generational way for new products. On top of that, there is ambiguity between the product lifecycle as interpreted in marketing and in sustainability-related contributions, making the definition of MLC vague (Östlin et al., 2009). Based on the limited number of sources that could be identified dealing with the topic at all, it further becomes clear that there is no established research terminology to delineate a cross-generational remanufacturing approach. Consequently, there is no holistic understanding as a basis to drive further research efforts in an organized way. Hence, we address this issue in the following by characterizing a specific approach, laying out a definition for cross-generational remanufacturing and providing an outlook for further research.

5 Cross-Generational Remanufacturing for Forward-Looking Circularity

Especially the work by Hapuwatte et al. (2022) has shown that the concept of cross-generational remanufacturing for the primary market holds strong potential both in terms of economic benefit for manufacturers and ecologic advantages to foster more sustainable products. The general notion to consider multiple generations is already present in the general Eco-design guidelines (Belli and Quella, 2021). However, this does not go beyond a general remark. It is here crucial to understand the difference between pure multi-lifecycle thinking and cross-generational thinking (cf. chapter 1): While the first relates to bringing products into (any) new lifecycle in general, cross-generational thinking relies on advanced forward-looking planning across multiple generations. This approach necessarily must be thought proactively in the product engineering stage to not be reliant on improvisation in the production stage. We hence suggest an approach based on the notion of CG thinking as used in the model of SGE - System Generation Engineering, which is characterized and defined in the following to answer the second research question.

5.1 Defining Cross-Generational Remanufacturing

Given the current research landscape is fragmented and has not established a standardized nomenclature for the suggested approach, we aim to establish a uniform terminology. As mentioned previously, CG-Remanufacturing can be seen as a specific strategy under the umbrella of MLC. To derive a holistic definition, we investigated more comprehensive representatives of the numerous definitions for conventional remanufacturing from the fields of research (Haynsworth and Lyons, 1987; Ijomah et al., 2004), industry (ANSI RIC001.1, 2017) and society (World Bank (Lund, 1985); United Nations IRP, 2018). An overview of covered key aspects in these definitions is shown in Table 1.

Table 1. Common definitions of remanufacturing and analysis regarding covered aspects

Aspect *(explicitly mentioned)*	Lund, 1985; Haynsworth & Lyons, 1987	Ijomah et al., 2004	ANSI, 2017	UN IRP, 2018	CG-Reman
Process character	✓	✓	✓	✓	✓
Industrial scale	✓		✓	✓	✓
Input: used/worn product/core	✓	✓	✓	✓	✓
Output: product with performance/quality equivalent or better than original new product	✓	✓	✓	✓	✓
Full original warranty		✓		✓	
Individual process characteristics/steps	✓		✓ (referenced)		
Customer’s perspective as determinant		✓			✓
Standardization/control of process			✓	✓	

The table also highlights the aspects that we deemed relevant for the definition of CG-Remanufacturing. In addition to integrating the common first four aspects with the cross-generational approach, we included the customer and user perspective as determinant for evaluation of the resulting product following the definition of Ijomah et al. (2004). Taking these insights into account, we define Cross-Generational Remanufacturing (CG-Reman) as follows:

> *Cross-Generational Remanufacturing is a 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. From the customer and user perspective the generated products/systems are offered on the primary market with additional inherent sustainability.*

Hence, this definition extends beyond conventional remanufacturing through the planned and anticipated transfer into the latest generation (cross-generational) and the offering of the final product on the primary market. We use the broader understanding of remanufacturing as a process on product-/system-level which includes strategies such as component reuse, i.e. the components/subsystems used in the CG-remanufactured product have been restored by a degree of $0\% \leq x\% \leq 100\%$, where 0% equals direct component reuse and 100% would indicate a newly linear produced subsystem, depending on the return condition of the core. Crucially, the customer always buys the CG-remanufactured product on the primary market (i.e., as a completely new product). This can be supported by new regulative standards that already take the direction of aiming for less labeling obligations for products with remanufactured parts (e.g., DIN SPEC 91472 (2023)). Even more critical than for conventional remanufacturing are appropriate business models like product-as-a-service, to ensure a defined quality of returned cores (cf. e.g., Chierici and Copani, 2016). Given the importance of product design to enable such an approach, CG-Reman might be enabled by cross-generational commonality or at least compatibility (cf. chapter 4) as example elements of more holistic Design for Cross-Generational Remanufacturing (DfCGRem) guidelines, which are currently being researched and further developed. Here the model of SGE provides a promising approach to support the analysis and synthesis of products by linking the complex cross-generational interdependencies in a planned and anticipated manner, and in identifying components that have the highest potential for CG-Reman based on their variations over time.

5.2 Identifying Suitable Products for CG-Remanufacturing

In remanufacturing literature, product diffusion curves are often used as a visual aid to describe the relationship of newly sold products and their return quantity available for remanufacturing (e.g., Debo et al. (2006)). Figure 3 shows such a curve qualitatively for a product where the ratio of the average time in use (used synonymously for average useful life) and time in market of the respective product generation is once close to 1 (A) and once very different (B). It can be seen graphically, that especially for products with a similar length of time in market and time in use a cross-generational component reuse holds significant potential to leverage components returning from the market (Östlin et al., 2009).

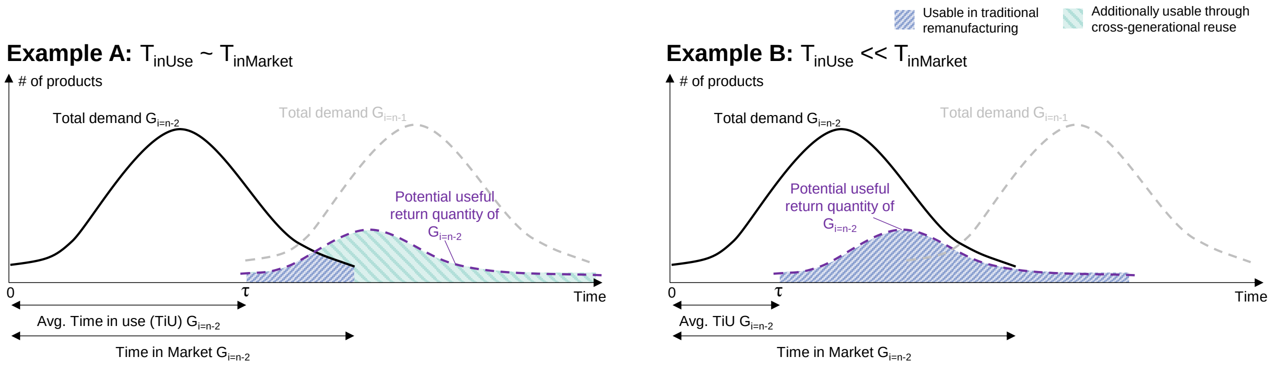

Figure 3. Diffusion curves for products with similar (A) and different ratio (B) of time in use and time in market (cf. (Debo et al., 2006; Östlin et al., 2009; Wang et al., 2017)

Hapuwatte et al. (2023) prove this intuitive relation with a mathematical model, which shows that benefits of intergenerational component commonality are highest when the ratio of average time in use and time in market is between 0.25 and 2. This metric provides relatively clear initial boundaries for products that could be particularly suitable for a "Design for CG-Remanufacturing" (DfCGRem). However, the absolute values of time in market and time in use are also important to consider, as literature suggests. Debo et al. (2006) identified slow-diffusing products (i.e., long time in market) as more suited for (conventional) remanufacturing, which can be explained through a higher likelihood of overlap between core availability from reverse product flow and product demand, especially with repeat-purchase products. Using the same metric, this observation translates into a smaller ratio of time in use and time in market is generally favorable for (conventional) remanufacturing (Hapuwatte et al., 2023). Hence, products with this characteristic should ideally follow "Design for Remanufacturing" (DfRem). With a similar logic but different metrics Suhariyanto et al. (2017) derive four groups of products and the corresponding suggested multi-lifecycle strategies in a two-by-two matrix. Notably, they link upgrading as a solution for products with fast evolution speed, which can best be translated to a high ratio of time in use and time in market. These products would hence most benefit from Design for Upgrade Remanufacturing (DfURem) (Wu et al., 2023). Focusing on the products suitable for CG-Remanufacturing, we propose an amended and more differentiated version of the matrix as presented by Suhariyanto et al. (2017), cf. Figure 4, which combines the previous insights graphically. The idea of this is to derive an initial classification of the first design strategy that should be pursued with priority depending on the high-level product attributes.

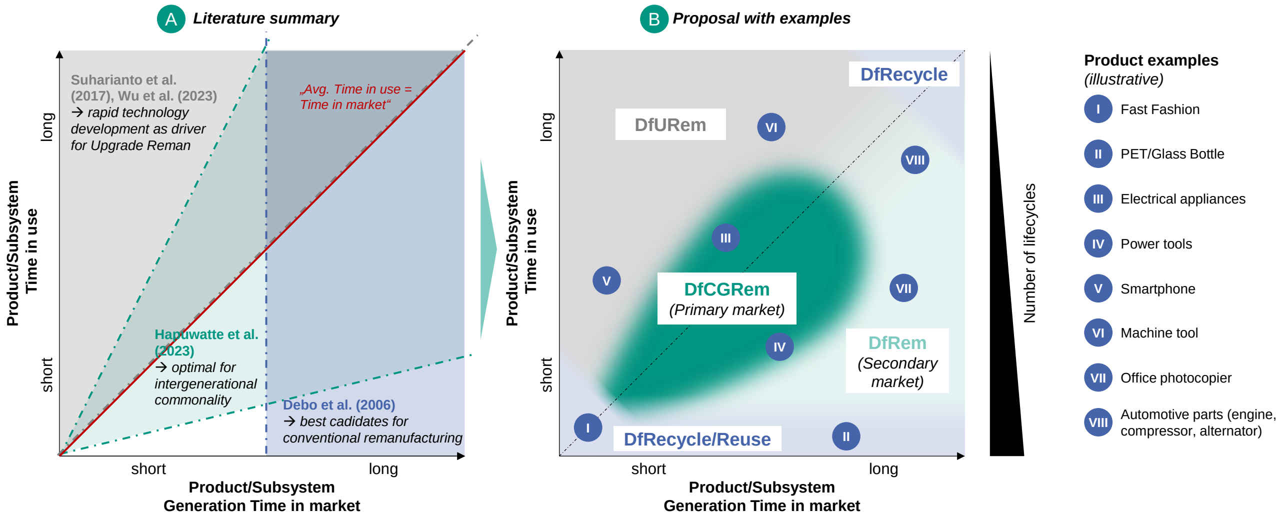

Figure 4. (A) Literature summary (Debo et al., 2006; Hapuwatte et al., 2022; Suhariyanto et al., 2017; Wu et al., 2023) and (B) proposal for circular design strategies to be investigated with priority based on product and market characteristics

While theoretically the entire area suggested by Hapuwatte et al. (2023) would be suitable, we acknowledge the limits of cross-generational design due to limited forecasting possibilities with very long time horizons. This also reflects the view of the presented literature on intergenerational commonality, which typically focuses on rather short-cycled products (Kim and Kim, 2020). While some case studies define this mainly with consumer electronics such as smartphones or PCs, we see more inherent potential in products that are not dominated by integrated circuit components, given that these are harder to remanufacture and typically have a shorter component time in market. On the other hand, in extreme cases that have both a very long time in market and very long time in use, there will likely be only a very limited opportunity to preserve value creation on the component level. Hence, Design for Recycling should be employed to ensure the more flexible circular flow on material level in a very distant future. At the same time, for extremely short-cycled products or those with extremely low time in use, Design for Reuse and Design for Recycling are likely the best options (Suhariyanto et al., 2017). In general, other circular strategies should always be considered as a secondary option if the first design strategy suggested is not feasible, with Design for Recycling as the default fallback option (cf. Bakker et al. (2014)). Exemplary products that could show the relevant characteristics are added to the matrix for illustrative purposes, we deem the approach most appropriate for mechatronic products. Together with the definition derived in chapter 5.1, we have answered RQ2 through this analysis of suitable products.

6 Conclusion & Outlook

In this paper we analyzed the current state of literature regarding cross-generational remanufacturing (CG-Reman) through a systematic literature review amended with explorative search. We could identify initial contributions in this field, especially papers with an operations research character that highlighted the potential benefits of such approach. Explicit proactive design support literature was rare and only showed adjacent concepts, that still are valuable input for the approach in question. Based on this, we presented characteristics and a definition for CG-Reman as a forward-looking process based on established definitions for conventional remanufacturing and the concept of CG thinking. We further narrowed down the product types that this approach might be especially suitable for and highlighted the potential of the model of SGE to further develop the approach. This forms the foundation to develop methodological support for cross-generational remanufacturing, which is currently being investigated by the authors and will be presented comprehensively in future publications. This can eventually lead to a consistent integration into future product engineering to create mutual benefits for both OEMs and end-customers. Since current products are not designed according to a DfCGRem, a transition phase until such approach can leverage its full potential in practice is inevitable. Hence, clarity of a concept and a focus area to find suitable use cases as suggested by this contribution can serve as initial step to bring the approach into practice.

The limitations of this paper are related to the lack of uniform language in literature, hence there is an inherent difficulty to ensure complete coverage. We tried to minimize this risk with a combination of synonymic keywords and additional explorative search. Ultimately this highlights the need for a consistent definition and unified nomenclature of the concept. Furthermore, this contribution only presents and describes a concept, which requires further development as mentioned above to create a technical feasible and economically proven solution.

Future research should leverage the insights from existing literature identified in this contribution, e.g. on product family design and modularity, to develop a holistic design support. This should ideally be done using a product that has a similar time in use and time in market, which we identified as especially suitable for CG-Reman. As part of this it will also be crucial to understand not only which product categories, but also which components in these products are especially suitable and how they should be designed to maximize the potential of the approach. Additionally, the development and tailoring of suitable and existing circular business models to CG-Remanufacturing should be pursued.

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