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Circularity in product engineering - towards a forward-looking approach across product generations

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Abstract

To enable a truly circular economy in product engineering, the development of products in generations must be considered. Thus, we strive to enable a forward-looking circularity approach, proposing the integration of system generation engineering (SGE) with circular economy principles. By analysing the qualitative interrelations among product generations driven by distinct value preservation strategies on various value creation tiers ("R-strategies"), we extend prior SGE research to advance model theory and support practical application of circular product engineering.

Keywords: *product development, circular economy, sustainable design, system generation engineering, design models*

1. Introduction

The imperative for advancing ecological sustainability is increasingly evident in both research and practical applications, driven by external factors such as the escalating impacts of climate change, evolving stakeholder requirements, and expanding market potential (United Nations, 2019). The concept of a circular economy (CE) has emerged as an approach, e.g., to curtail resource consumption and mitigate energy demands within production processes. The inherent idea of the circular economy is to be *"an industrial system that is restorative or regenerative by intention and design"* (Ellen MacArthur Foundation, 2013). However, approaches found in practice often show a rather reactive approach can lead to a variety of challenges (Shahbazi and Jönbrink, 2020): Anecdotal use cases are found for existing products after their creation and use (e.g., upcycling or repurposing), new products are created in reactive manner from recycled materials without considering their onward use (e.g., sneakers from ocean plastic, cf. adidas (2023)) or products are remanufactured ex post by third-party entities and sold on the secondary market (e.g., starters and alternators). While initial successes are achieved proving the potential of a consequent CE adoption (Zomer *et al.*, 2022), current efforts often still perpetuate the downward spiral of a cascaded use, wherein the value generated diminishes in each successive cycle, merely extending the time before eventual disposal in landfills (Singh and Ordoñez, 2016). To counteract this, we suggest considering a holistic view on product engineering in practice in conjunction with CE (Pigosso and McAloone, 2017; Pozo Arcos *et al.*, 2018). Hence, to create enduring value that resonates with customers, we believe it is integral to include a forward-looking perspective on circular strategies, that includes a temporal dimension across product generations. Since the latter is a key element of the model of SGE – System Generation Engineering as introduced by Albers *et al.* (2015), we use it as a basis for our research. This paper explores how different circular strategies can be reflected in the model of SGE and how this can be used for practical applications. To accomplish this objective, existing elements within the SGE framework are subjected to further structuring and refinement.

2. Research background

2.1. Sustainability in product engineering and circular economy

A decoupling of value creation from resource consumption through a transition to circular economy is crucial to achieving the Sustainable Development Goals (SDGs), given the finite nature of natural resources (Diaz *et al.*, 2021). The circular economy (CE) as defined by Ellen MacArthur Foundation (2013) replaces the linear economic model known as end-of-life or take-make-waste (Cudok *et al.*, 2022) by renewing, reducing, reusing, recycling, and recovering materials (commonly referred to as R-strategies) (Kirchherr *et al.*, 2017). An early and comprehensive consideration of the circular economy achieves strong reductions in environmental impacts as well as an extension and intensification of useful life (Albæk *et al.*, 2020). Product engineering, which encompasses the entirety of product planning, product development and production system development (Albers and Gausemeier, 2012) is assigned a key role to create more circular products (Shevchenko and Cluzel, 2023), since up to 80 percent of the environmental impacts of a product are determined in the early development phase (Eigner *et al.*, 2014). The difficult transition from circular waste management to a product-oriented CE in practice is challenged by the lack of concrete targets, especially for the initial phases, prevention, and preparation for circularity in product development (Diaz *et al.*, 2022). Currently, the circular economy is often only considered retrospectively at the end of the product life cycle (Schulze *et al.*, 2023; Shahbazi and Jönbrink, 2020). To develop a sustainable and circular product that causes as few negative environmental impacts as possible and has a long useful life, embedding model-based support for the implementation of CE strategies in product development is necessary (Diaz *et al.*, 2022).

There is currently a multitude of circular strategies in literature, typically reflected by R-strategies, which can be classified and clustered according to various criteria, e.g., by the degree of dismantling or based on the proportion of product and material recycling (Potting *et al.*, 2017). However, due to the large number of strategies, there is no uniform understanding, which also has an impact on the implementation and application in product development (Geissdoerfer *et al.*, 2017). A well-known and established framework is the circular economy system diagram, known as the butterfly diagram by the Ellen MacArthur Foundation (2015), which introduces the following four tiers based on their value preservation level: Maintain / Prolong, Reuse / Redistribute, Remanufacture / Refurbish and Recycle. Referring to further approaches, the number of strategies considered differs significantly, so that sometimes more than 10 or only two to three R-strategies are considered (Becker *et al.*, 2019; Potting *et al.*, 2017; Reike *et al.*, 2018; Kirchherr *et al.*, 2017). The reasons for the different number of R-strategies considered are manifold and include, on the one hand, the partly non-uniform definition of the terms used to describe the R-strategies and the partly different interpretation as well as the degree of abstraction used as a basis for the analysis (Kirchherr *et al.*, 2017). Blomsma *et al.* (2019) conducted a systematic literature review on circular strategies and developed the circular strategies scanner, suggesting a sum of 32 circular strategies to support the realization of CE in practice. This paper refers to the circular economy system diagram of the Ellen MacArthur Foundation (2015) as it is sufficient for the purpose as well as established and used in academia and practice.

Circular business models have been investigated as an approach to integrate CE principles with business operations in practice. Based on the a differentiation between slowing and closing loops, Bocken *et al.* (2016) suggest six generic business model strategies. However, most product engineering models for the CE are based on existing approaches from the field of EcoDesign or Design for Sustainability (Bender and Gericke, 2021). While these approaches focus primarily on the linear economy (slowing or narrowing loops), the product engineering models for the CE should focus on the consideration of value, quality and material over several product life cycles to close resource flows (Schulze *et al.*, 2023; Bocken *et al.*, 2016). To achieve a circular product design for multiple life cycles, circular strategies must be taken into account in the early stages of product engineering (Kadner *et al.*, 2021). Different approaches can support this, such as various "Design for X"-Methods, EcoDesign frameworks or models for achieving circular systems (Pozo Arcos *et al.*, 2018). In literature, methods for design for recycling, approaches to the design of repairable and maintainable systems as well as the consideration of product-service systems are currently most relevant (Aguiar *et al.*, 2022). In connection with the product engineering process, previous studies have mainly focused on the effects of circularity on only one product generation without taking the development of product in generations explicitly into account (Gräßler and Hesse, 2022; Becker *et al.*, 2019; Hollander *et al.*, 2017; Breimann *et al.*, 2023; Stölzle *et al.*, 2023). Hence, current implementation and operationalization as well as model-theoretical support in product engineering for an effective cross-generational approach is limited (Dokter *et al.*, 2020). The model of SGE - System Generation Engineering provides an advantageous basis for integrating circular criteria into product engineering over several product generations (Schulze *et al.*, 2023).

2.2. System Generation Engineering

To systematically describe the generational nature of product development, Albers *et al.* (2015; 2022) developed the model of SGE – System Generation Engineering (formerly: PGE – Product Generation Engineering). The central idea is that new products or systems are never developed from scratch but based on internal (e.g., previous generations) and external references (e.g., competitor products). These are described as elements of an assembled reference system R_i (Albers *et al.*, 2019). The corresponding product generation is denoted as G_i, whereby the running index i=n indicates the generation currently in development that will be the next introduced to the market. $G_{i=n}$ is then developed from $R_{i=n}$ exclusively through three types of variation of reference system elements (RSE): The carryover variation (CV) describes the carryover of a RSE into a new system generation while allowing modifications solely to its interfaces to facilitate system integration. Attribute Variation (AV) describes the new development of a subsystem while preserving the underlying solution principle of the RSE and making alterations to attributes that define its function. New development by principle variation (PV) is constituted by a change in the solution principle of the RSE to fulfil the desired function (Albers *et al.*, 2015).

For the operative realization of product development, Albers and Meboldt (2007) defined the model of the system triple for product engineering based on Ropohl (1975). This encompasses the system of objectives, the operation system and system of objects. The system of objectives describes all explicit objectives for the product to be developed, their boundary conditions, dependencies, and interactions. It contains no physical objects and constitutes the repository of the confirmed knowledge and planning of product development. The operation system is a socio-technical system that connects the system of objectives and system of objects by performing transformations between them. Operation systems are composed of activities, methods and processes as well as executing resources, resources to be used, and their temporal dependency. Lastly, the system of objects contains the tangible and intangible artifacts created by the operation system. Product engineering can hence be understood as the iterative development of the system of objects by the operation system based on the requirements specified in the system of objectives (Albers and Meboldt, 2007).

According to Albers *et al.* (2019) the reference system generally contains *"elements [that] originate from already existing or already planned socio-technical systems and the associated documentation and are the basis and starting point for the development of the new product generation"*, which can also be something as abstract as an idea. To further organize and structure the reference system, Albers *et al.* (2024, Manuscript submitted for publication) used the previously described model of the system triple of product engineering. Consequently, they introduce three disjunct subsystems of the reference system. The *reference system of objectives* contains *"elements of the character of the system of objectives' elements. It is the basis and starting point for the development of the system of objectives of the new product generation* $G_{i=n}$*"*. The *reference operation system* and *reference system of objects*, contain elements of the character of the operation system and system of objects, and serve as the basis for the development of the operation system and system of objects of the $G_{i=n}$, respectively.

3. Research objectives

Based on the literature we identified that the model of SGE - Systems Generation Engineering holds promise for application in the domain of circular product engineering, as it is suitable to systematically describe product engineering across product generations. The idea of the reference system, that contains reference system elements that can be transformed through different variations into a new product generation, creates an advantageous premise to model different circular approaches across generations. Hence, we are using the model of the SGE as a foundation for our research and are looking at ways to integrate it with circular economy strategies. To lay a groundwork for these endeavours, our research

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objective in this paper is the development of a cross-generational approach for product engineering that helps to enable circular economy strategies. To this end, we employ a three-step approach, as delineated by the following research questions.
First, to facilitate a cross-generational description, the required information to employ different circular strategies, which have been reflected by R-strategies in academic literature and practice, needs to be identified. Consequently, our first research question is the following:

> *RQ1: How can the information required to describe different R-strategies in a cross-generational context be characterized?*

Building on that, the second challenge addressed in this paper is to shed light on the representation of value preservation cycles as an abstraction of R-strategies and the corresponding focal elements in the model of SGE. This exploration extends to a description of cross-generational circular product development as well as a description of the conceptual steering of cross-generational optimization within the process. This leads to our second research question:

> *RQ2: How can value preservation cycles be described with a cross-generational focus?*

Lastly, based on the concept of the reference system in the model of SGE, we seek to investigate methods for identifying initial circularity potential for RSEs by deriving a description model independent of specific solutions or decision-making. Given not all elements of the reference system will be suitable for a specific value preservation cycle, the last research question is the following:

> *RQ3: How can the reference system be used to identify initial circularity potential in product engineering?*

These research questions are presented sequentially due to their interdependence. By combining the insights derived from their respective answers, we aim to accomplish our overarching research objective. We will exemplify the relations using the example of an angle grinder, which is a handheld power tool used in industrial and private contexts. The example was chosen due to our expertise with its composition and as an easily understandable but sufficiently complex mechatronic product. Figure 1 shows the example system with hypothetical subsystems that will be used to illustrate our findings.

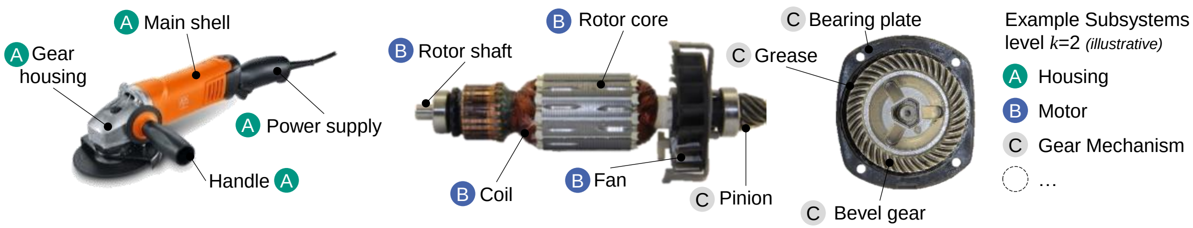

Figure 1. Example system of the angle grinder and illustrative subsystems

4. Circular System Generation Engineering

4.1. Separating cross-generational value preservation cycles

In literature, the previously described R-strategies (Ellen MacArthur Foundation, 2015) in chapter 2.1 are typically considered on product (or system) level and are ordered according to their level of decomposition (cf. Figure 2). The system level is defined through the system of objectives. On this level, we can assign them to either a focus within a single product generation (intra-generational) such as maintain/prolong and reuse/redistribute. This also applies to remanufacturing in the traditional sense. On the other hand, there are R-strategies that are not bound to a single product generation, such as recycling, and can be interpreted as cross-generational by design. Conceptionally, this is also possible for remanufacturing through the cross-generational reuse of subsystems (Wang *et al.*, 2017). It is important to note that when considered on subsystem level (i.e., any level below the defined main system, $k = 2...m$), the strategies of maintain/prolong and reuse/redistribute are inherent in the system-level remanufacturing activities (Mangun and Thurston, 2002). Given we are looking for cross-

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generational relations, strategies aiming to maintain/prolong the useful life as well as to facilitate reuse/redistribution on system level (i.e., the entire product $k = 1$) are not relevant for this paper due to their focus within one product generation. Given the low ecological advantage and no cross-generational benefit, the sometimes incorporated 'recover' is also excluded from our research focus (Potting *et al.*, 2017). Consequently, we can see that the strategies of remanufacturing and recycling show promising potential for cross-generational application on system level.

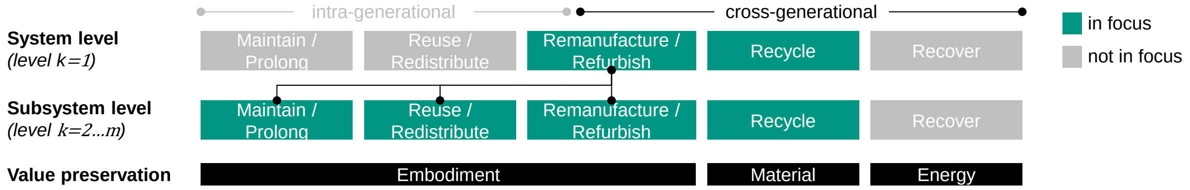

Figure 2. Abstraction of R-strategies for cross-generational view

To answer RQ1, we are looking for distinctive types of information that will be required for the cross-generational application of common R-strategies. Conceptually, the presented approaches can be classified on a high-level according to their value preservation in descending order, with each level containing the lower one: embodiment level (e.g., remanufacture, reuse, maintain), material level (e.g., recycle) and energy level (e.g., recover/incineration) (cf. Tolio *et al.* (2017), Blomsma *et al.* (2019)). Given our previously narrowed down focus of relevant R-strategies in our research context, we find that we can distinguish two layers of informational views on existing products as reference system elements, that are required to employ value preservation cycles: 'Material' and 'Embodiment'. To empower strategies such as recycling, information regarding the 'Material', such as type, grade and properties are important to enable cross-generational planning. With the lower level of value preservation there is also more versatility, as engineers are free to design new shapes or designs and only have to rely on material properties. On the contrary, reuse or remanufacturing of subsystems across product generations first and foremost needs information about the geometry, functional compliance, and technical specifications, which we summarize in the 'Embodiment' level. The same would also be true for the less common strategy of repurpose (Potting *et al.*, 2017), which can be interpreted as a variant of reuse in a new system context outside of the considered system generations. While material might likely play a role to comply with functional requirements and technical specifications and is thus partly implied in the 'Embodiment' level, it is here only a means to an end. To summarize, the differentiation into 'Embodiment' and 'Material' can guide the cross-generational description of relevant value preservation cycles for product engineering, answering our first research question.

4.2. Describing cross-generational value preservation cycles and circular product engineering in the model of SGE

To describe a cross-generational approach to circular economy, we take a two-step approach: First, we derive a representation of the cross-generational value preservation cycles in the model of SGE based on the generalized views introduced in chapter 4.1. Building upon that, we explore the process of describing and optimizing cross-generational circular product engineering.

Cross-generational value preservation cycles in the model of SGE

Given we are looking at the way that product generations are linked to each other, we focus on the reference system and a way to structure it with the goal of modelling value preservation cycles. As discussed in chapter 2.2, the reference system can be divided into three distinct systems analogue to the system triple. To describe interrelations based on physical representations of reference system elements, our focus is on the reference system of objects. While this also contains elements that are virtual or immaterial (e.g., bits of information or design sketches), we focus on the elements with physical representations (e.g., the previous product generation). It can be seen from chapter 4.1 that the enabling of cross-generational value preservation cycles requires two levels of information. Hence, we introduce this split in the reference system of objects by creating a 'Embodiment' and 'Material' view, which can be envisioned as two distinct views on existing physical entities as reference system elements. For

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example, the enclosure of an angle grinder from the previous generation can be both seen as the enclosure with the specific geometry and functional properties as well as a source of material if recycling is to be employed. This dual view provides a holistic information basis by laying out a set of options for theoretically possible value preservation cycles agnostic of any assessment.

If we now want to describe what cross-generational value preservation with a forward-looking intent looks like, we can use the model of SGE (cf. Figure 3): The reference system of the product generation in development $G_{i=n}$ is populated with reference system elements from different sources. Those that have a physical representation, e.g., the angle grinder of the previous generation $G_{i=n-1}$, will be part of the reference system of objects. As described, these elements can be interpreted both from a material or embodiment view. By using variation operators, elements of the reference system of objects are transformed into the generation in development $G_{i=n}$. From there, the same logic continues for upcoming generations, such as $G_{i=n+1}$ and $G_{i=n+2}$. If we now consider the representation of different value preservation strategies in this model, we can see that they can be separated through their association with the previously described specific views of RSEs in the reference system of objects. The level of value preservation can be changed with every generation if planned accordingly (e.g., the bevel gear could be initially remanufactured for reuse in $G_{i=n+1}$ and $G_{i=n+2}$, but then be recycled for later product generations due to too high degradation). Through the conceptual cross-generational linkage of the reference systems of subsequent product generations in the SGE, a forward-looking intent will be required in the successful operationalization of cross-generational value preservation cycles.

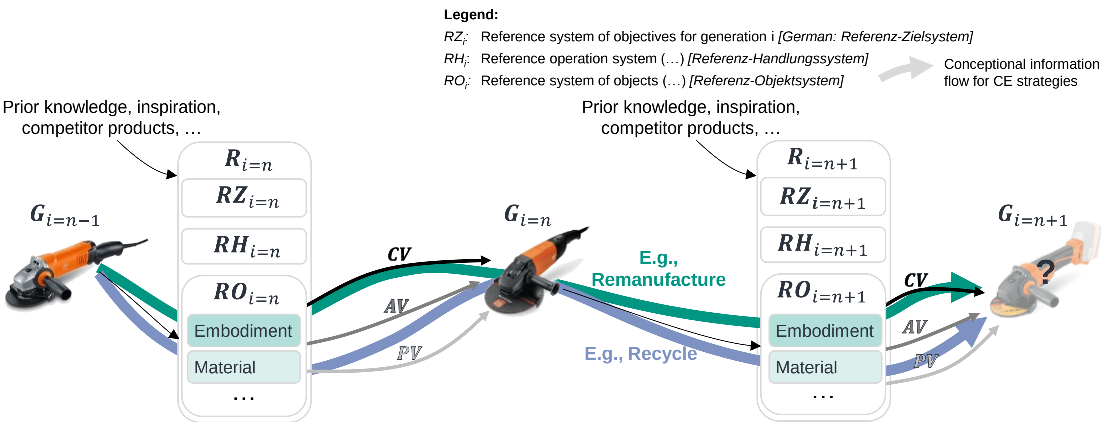

Figure 3. Qualitative information flow for selected cross-generational value preservation cycles in the model of SGE

Furthermore, there is a likely connection between different value preservation strategies (remanufacturing and recycling) and the variation types: By their definition and logical reasoning, it can already be seen that a principle variation or significant attribute variation can hardly preserve physical embodiment, meaning that a variation of one of these types would typically be related to material preservation, if at all possible. On the contrary, remanufacturing or reuse of subsystems will likely go along with a carryover variation. The exact relationships are subject of further research.

This cross-generational conceptional linkage, which can be operationalized e.g., by using systems engineering software, enables engineers to pursue a closed-loop circularity across generations. This is especially advantageous for those value preservation cycles on the embodiment level, given the lower likelihood of successfully repurposing subsystems in another context. Still, on the material level cross-generational recycling can also be a favourable effort to make sure that the material created as a leftover by one generation will have an actual use in future products. It is noteworthy that, since we are looking at a product engineering model, the flows in the graphic only describe an enablement through respective product design rather than the actual realization.

Circular product engineering

We have now seen that the model of SGE can be used to describe and plan value preservation strategies across product generations. However, this alone does not give any information regarding their

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meaningful application in the development of a specific product generation and how this steering process can be conceptually described. We therefore want to explore the model of the system triple to shed light onto the process-related interplay for cross-generational circular product engineering of a specific generation in development ($G_{i=n}$). An overview of this process is depicted in Figure 4 and explained in the following.

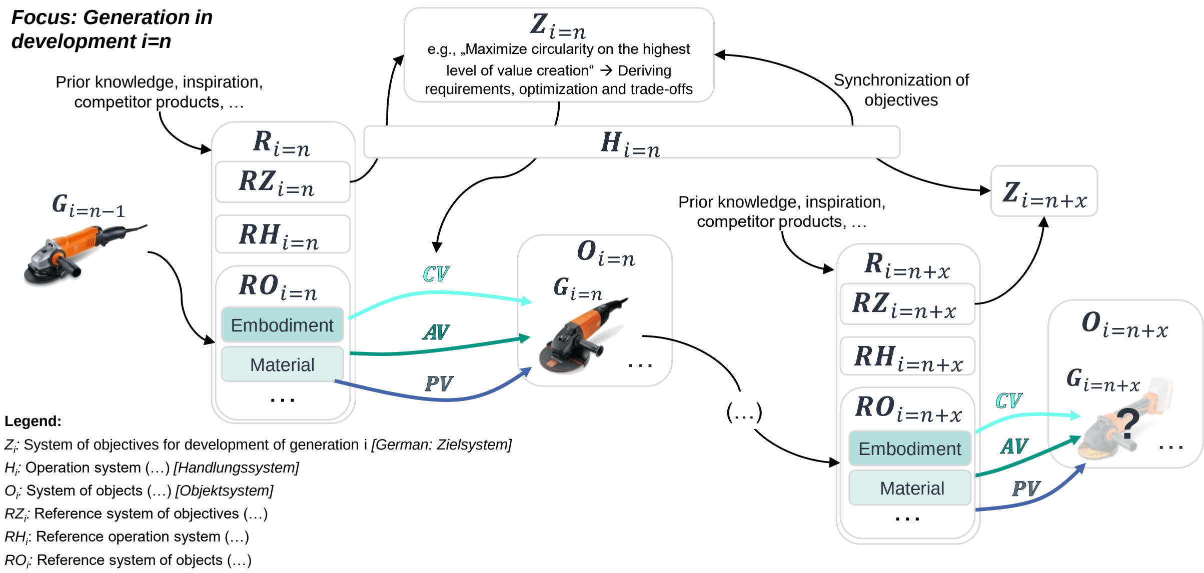

Figure 4. Relations and process-related interplay for circular product engineering

To contextualize the set of options for leveraging theoretical value preservation that can be derived from the two views in the reference system of objects ($RO_{i=n}$), first and foremost the objective for circular product engineering needs to be targeted. This is part of the system of objectives ($Z_{i=n}$) for a specific product generation $G_{i=n}$. Given that the optimization will likely be more beneficial if spanning across more than one generation, this also needs to be anchored into the future generation's systems of objectives ($Z_{i=n+1}$, ..., $Z_{i=n+x}$), which need to be synchronized with the current system of objectives by the operation system ($H_{i=n}$). In practice, this synchronization may lead to (subsystem) designs with anticipative or over-specified features that might not be required for the single application within the current generation in development $G_{i=n}$, but for 'Embodiment' reuse in future generations $G_{i=n+x}$ (e.g., connection points, extended subsystem useful life).
Since the input for product development typically comes with a variety of objectives and requirements (e.g., customer/regulatory requirements, realization constraints), there will likely be secondary conditions that could limit the fulfilment of the optimization criterion for circularity. For the angle grinder this could be the requirement to move from a cable-bound device to a battery powered solution, which will also impact the power train. It becomes obvious that this would be a hindrance for maximizing circularity due to reduced value preservation possibility. Hence, trade-offs need to be found by the operation system to shape a consistent system of objectives through iterative alteration. The exact approach how this can be achieved is subject of further in-depth research. Based on this set of objectives including the trade-offs between them, the operation system transforms selected elements of the reference system of objects into $G_{i=n}$, using the three variation operators of carryover, attribute and principle variation. Given these elements will be part of the reference system of objects of the next generation due to the repetitive character of the model of SGE, this concludes the description of circular product engineering for a specific generation and thus completes the answer to RQ2.

4.3. Deriving circularity potential in product engineering

From chapter 4.2 we have seen that the split into a 'Material' and 'Embodiment' view provides us with a theoretical set of options for cross-generational value preservation cycles. To translate this into first

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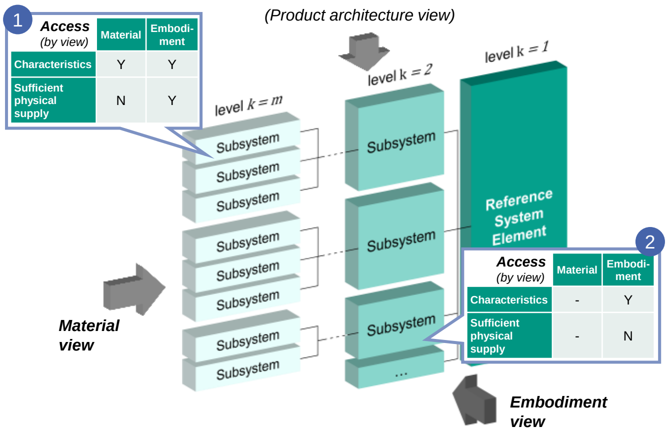
actionable insight, we now apply the previously described relationships within the model of SGE to identify initial value preservation potential based on an initial assessment of RSEs.

So far, we have only structured the reference system of objects with the necessary condition for the different value preservation cycles. Still, when we look into practice, not all (physical) elements of the reference system of objects will be equally or at all suitable for circular strategies. Hence, another piece of information is required: In the context of deriving actual circularity potential, the role of RSEs needs to be more than inspiration or design reference, but also include information about realizable and sufficient physical supply: If a subsystem is not possible to source for physical value preservation, there is no purpose in designing for this case. By default, sufficient physical supply is not guaranteed for every RSE. We therefore introduce 'Access' as an RSE attribute, that describes the sufficient condition to qualify the potential for cross-generational value preservation strategies.

'Access' describes a solution-agnostic and view-dependent attribute of elements in the reference system of objects with two values (true, false) and relates to both the access to (view-dependent) characteristics and (possible) access to sufficient physical supply (stored as information in the reference system). Both must be given for 'Access' to be true (cf. Figure 5). Access to information about characteristics encompasses necessary aspects to describe a physical RSE regarding the respective view: For 'Embodiment' view this could be geometric information or technical specifications, for the 'Material' view the properties of the used material. Access to information (and corresponding certainty) about sufficient physical supply describes the possibility to gather the respective RSE in scalable quantities, that are relevant in relation to the production quantity. In addition, through the iterative evolution of the reference system, efforts can be taken to change the value of access for specific RSE.



Access {material/embodiment}	**Y**	**N**		
Characteristics	Y	Y	N	N
Sufficient physical supply	Y	N	Y	N

Example 1
- Subsystem (level m) from previous generation with information about both material and embodiment characteristics and possibility of sufficient physical supply, but made from non-recyclable material (hence only physically accessible on embodiment level)

Example 2
- Subsystem from competitor product with information about embodiment characteristics (e.g., through reverse engineering), but without possibility of generating physical supply in relevant quantities

Figure 5. Overview of the physical reference system element attribute 'Access'

While the aspect of access to characteristics can be strongly linked to the internal or external nature of an RSE, which has been previously described (Albers *et al.*, 2017), it is not equivalent: For most internal products access to characteristics information will typically be given, access to sufficient supply however is not guaranteed: While on the one hand it must be ensured to gather sufficient supply of old product generations, access to supply can also be limited due to (current) technological or economic reasons, e.g. non-recyclable materials (cf. Figure 5, Example 1). For external reference system elements, access to information about characteristics may be acquired (e.g., through teardowns, reverse engineering), however access to physical supply might be limited (e.g., if they originate from competitor products, Example 2). In contrast, external products that suppliers might be offering for reuse could be reference system elements with both accessible characteristics and supply. Note that the same physical element can fall into different access categories depending on the ‘Embodiment’ or ‘Material’ view. It is also important to understand that the 'Material' view can only see the lowest subsystem level k=m with mono-material subsystems.

If we look at the derived structure of physical elements in the reference system of objects, we can now create three distinct groups, that can be interpreted as subsets of the reference system of objects in a mathematical sense. First, there is a group of RSEs that has potential to be circulated on a ‘Embodiment’ level, e.g., through reuse, remanufacturing, or repurposing. This group is constituted by the reference

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system elements described from the 'Embodiment' view (necessary condition) and where access to information about both characteristics and supply is given (sufficient condition). For the generation in development, we call this subset the Embodiment-Preservation-Subset ($EP_{i=n}$). Second, some RSEs show potential to preserve their value on a ‘Material’ level. Just like before, these are elements that are characterized by a 'Material' view on a physical representation and are having a *true* access variable for this view. This subset is denoted as Material-Preservation-Subset ($MP_{i=n}$). Lastly, there are RSEs that fulfil the necessary condition of a representation in ‘Embodiment’ or ‘Material’ view but are not accessible regarding information either about characteristics, sufficient physical supply, or both. These can still be valuable sources of other information, however, do not show initial potential to be employed in value preservation strategies. Hence, (sub-)systems of the $G_{i=n}$ based on these RSEs will have to be produced entirely new both regarding embodiment and primary material. This group is correspondingly called Non-Preservation-Subset ($NP_{i=n}$). Consequently, reference system elements belonging to $NP_{i=n}$ can (but don’t have to) be freely adjusted by the engineer without negative consequences for the value preservation. It is important to understand that while the subsets of $EP_{i=n}$ and $MP_{i=n}$ can have overlaps (e.g., subsystems that show both potential for reuse as well as recycling), the subset of $NP_{i=n}$ is disjunct from the other two sets. As mentioned before, the affiliation of an RSE to one (or several) of the subsets is not static, but can be strategically influenced, e.g., through additional efforts to acquire access.

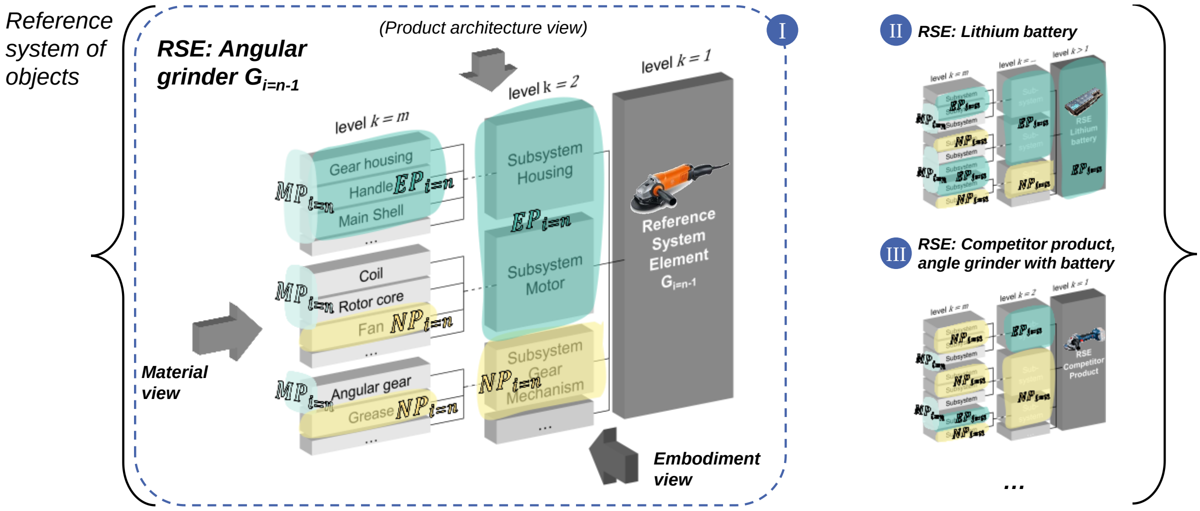

Figure 6. Visualization of potential-defining subsets of the reference system of objects

To visualize these subsets in a practical way, we once more employ the illustrative example of the angular grinder (cf. Figure 6, Figure 1). For the generation in development $G_{i=n}$, exemplary RSE could be the previous generation $G_{i=n-1}$ (I) that is currently being sold, a lithium battery (II) to create a cordless version as well as a competitor product (III). All of them would contain subsystems and elements that finally constitute the three subsets $EP_{i=n}$, $MP_{i=n}$ and $NP_{i=n}$. From the example RSE $G_{i=n-1}$, we can see that it can be decomposed into subsystems such as the housing, the gear mechanism, and the motor. The housing subsystem could be preserved on embodiment level both on an aggregate basis as well as in its individual parts, e.g. only the metal gear housing part. Hence, all elements are part of $EP_{i=n}$. At the same time, the individual housing parts could be preserved on material level through recycling to obtain raw materials like metal or thermoplastics. The motor subsystem shows initial potential to be preserved on embodiment level in its entirety since it is accessible both for information and supply, as it can be disassembled from the housing. However, on a lower-level $k=m$ there is no initial potential for embodiment preservation: The coil cannot be disassembled non-destructively from the rotor but could be preserved as material ($MP_{i=n}$). The same is true for the rotor core. The fan mounted on the rotor shaft is made from thermosetting polymer, which cannot be recycled to its original form. At the same time, in the $G_{i=n-1}$ it was designed in a way that it cannot be disassembled from the rotor shaft without being destroyed. Hence, the fan is part of $NP_{i=n}$, as it is not accessible both for the material and embodiment view as an individual item. For the example, we assume that mechanical failure of the bevel gear is the typical failure point for the angular grinder. Hence, we cannot ensure sufficient access to physical supply

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of the gear mechanism as a whole, and it is part of $NP_{i=n}$. Still, on a lower level the bevel gear could be preserved on material level ($MP_{i=n}$). For a new design there might be potential to extend the useful life of this subsystem to reuse it across multiple generations to make it part of the $EP_{i=n+1}$. The grease for the gear mechanism as a consumable is typically not preservable and thus part of $NP_{i=n}$. The example highlights that the assignment to the subsets is not inheritable over subsystem levels and needs to be evaluated individually. With a similar reasoning, $EP_{i=n}$, $MP_{i=n}$ and $NP_{i=n}$ are populated from all physical RSEs in the reference system of objects and then serve as a basis for a value preservation solution space. The separation into the subsets of $EP_{i=n}$, $MP_{i=n}$ and $NP_{i=n}$ can help to derive an initial potential assessment for individual RSEs regarding their application in circular value preservation strategies but independent of their actual realization, thus delivering an answer to our RQ3. Furthermore, a segmentation like this can help to nudge engineers to more sustainable design choices, by providing an overview of potential options to preserve existing value in the early phase of a new product generation's development (e.g., $G_{i=n}$, $G_{i=n+1}$). When optimizing for circularity, a positive feedback loop of a growing number of RSEs with initial circularity potential in each subsequent generation is created. However, it is also possible to use this delineation as a general description model within SGE that could enable (retrospective) analysis of circularity effectiveness of (older) product generations (e.g., $G_{i=n-2}$), e.g., by evaluating the share of a product generation that has been derived from $NP_{i=n}$.

5. Conclusion & outlook

The research objective of the presented work was to establish a conceptual foundation for a forward-looking and cross-generational approach to circular economy strategies from a product development perspective. To achieve this, we first found that a separation in value preservation levels according to 'Embodiment' and 'Material' is a suitable delineation for cross-generational application (cf. chapter 4.1). Second, conceptually represented these abstract value preservation cycles in the model of SGE based on the introduction of views in the reference system of objects for physical RSEs. Additionally, we described the logical links to understand the conception of circular product engineering in the model of SGE (cf. chapter 4.2). Lastly, we build upon these insights to derive a description model within the model of SGE that can be both applied for analysis as well as identification of value preservation potential during product development (cf. chapter 0). The latter was also a demonstration of a first practical application for circular product engineering based on the model of SGE.

The contribution to academia of this publication is a foundation for research opportunities to both advance the theory and enable its methodological application. This includes the challenges of developing an approach to deal with trade-offs in the objective system when leveraging value preservation potential, creating links between variation operators in the model of SGE and suitable R-strategies as well as modelling the cross-generational interdependencies with model-based systems engineering (MBSE) tools. These model-theoretical challenges are currently being tackled by the authors of this publication and can build on previous work such as for selection of R-strategies (e.g., Pozo Arcos *et al.* (2018)). The linkage of CE with the cross-generational thinking can also be used as a starting point to develop methodologic support for specific cross-generational R-strategies. Lastly, the evaluation of component shares from the respective reference system subsets could support a new approach for a priori cross-generational circularity assessment.

As implications for practice, this work has shown that strategic product planning can consider objectives of future product generations and align them with the generation currently in development, which includes an overview of future use and modifications of subsystems as well as the alignment with future validation and production systems. Additionally, the importance of conscious selection of reference system elements for product development has been highlighted. However, the limitation of this paper is its conceptual nature, which reduces the direct applicability of the presented results. To counteract this, the analysis of initial value preservation potential based on the three subsets will be evaluated and further refined through a more practice-oriented case study.

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