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Cross-Generational Variation Analysis to Identify Circularity Potentials based on the Model of SGE – System Generation Engineering

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Abstract

Circular product engineering is regarded as a key lever to decouple economic growth from resource consumption while preserving competitiveness. However, the transition from linear to circular product engineering of mechatronic systems requires balancing two seemingly opposing goals: Closing industrial material cycles while simultaneously maintaining high innovation potential across system generations. Existing development approaches scarcely reveal how variations across system generations affect circularity potential. This paper introduces an extended description model based on the model of SGE – System Generation Engineering that formalizes the variation between system generations of mechatronic systems. This work builds on the model of SGE and extends its variation operators with characterizing core factors. The description model provides a methodological foundation for systematically describing and analyzing cross-generational variations and aims to support prospective planning of circular development and value-retention paths. For practical grounding, three angle-grinder generations were systematically dismantled and analyzed. The case study demonstrates the applicability of the model and highlights its value for identifying circularity-relevant variation patterns. The work establishes a methodological basis for the analysis and prospective planning of circular development and value-retention paths within strategic product development.

Keywords: Product Development, Design Methods, Design Management, Circular Economy, Circular Product Development

1. Motivation

In 2018, 9.1 % of global material use was covered by secondary materials; by 2024 the share had fallen to 6.9 % [1]. This downward trend occurs against the backdrop that global resource use could increase by 60 % between 2020 and 2060 if predominantly linear value creation patterns remain unchanged [2]. At the same time, in addition to rising consumer demand, shortening technology and product life cycles intensify the pressure on firms to innovate. Circular product development is widely regarded as a key lever to decouple economic growth from resource consumption while maintaining competitiveness [3]. However, the potential of secondary materials remains largely untapped [1], [4]. Common activities within the concept of eco-efficiency pursue the goal of "doing more with less", yet are considered reactive and remain rooted in linear value-creation patterns [5]. This reluctance is further reinforced by limited customer acceptance in the market and concerns about cannibalizing the primary market targeted by manufacturers [4]. The transition from linear to circular product engineering requires balancing two seemingly opposing goals: Closing industrial material cycles while simultaneously maintaining high innovation potential in the face of changing market needs and technologies [6]. In this context, we see a need for approaches that can describe, analyze, and prospectively plan circularity across product generations. The model of SGE –

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System Generation Engineering [7] offers opportunities for integrating circularity across product generations within development processes [8]. However, numerous approaches are limited in practical application and, more importantly, as foundation for the strategic planning of products meeting future technologies and user, customer and provider benefits in the context of circular product engineering.

To address this gap, the present work utilizes the model of SGE and extends it to enable the analysis of circularity potentials and corresponding development and value retention paths. To meet this goal, a literature analysis is conducted to identify relevant factors for assessing circularity. Further, a systematic teardown of power tool generations is done to acquire system understanding and collect relevant data. Finally, we develop the extended model based on the model of SGE and apply it to the investigated power tool generations.

2. Related Work

2.1. Circularity in Product Engineering

The circular economy is widely regarded as a key lever to decouple economic growth from resource consumption [3]. In contrast to the linear take-make-dispose paradigm, circular industrial processes aim to establish an industrial metabolism [9], in which products and materials are treated as nutrients rather than waste [5]. A substantial share of a product's environmental impacts is determined during the early design and development phases [10]. Consequently, the three main task areas of product engineering – strategic product planning, product development, and production system development – provide leverage points for embedding circularity into product engineering [8].

In this work, circularity is understood as the degree of alignment with a systemic approach that maintains a continuous flow of resources and supports decision-making for sustainable product lifecycles [11]. To operationalize circularity, a variety of strategies have been proposed to close material loops and reduce the consumption of primary resources. Prominent examples are the so-called R-strategies, such as the 9R framework [12], which classifies strategies by their degree of circularity. The ELLEN MACARTHUR FOUNDATION [3] distinguishes between biological and technical nutrients, describing restorative circularity through cycles of maintenance, reuse/redistribution, refurbishment/remanufacturing and recycling in the technical domain. In regards to activities in product engineering, Albers et al. [8] propose a higher-level classification of preservation cycles; It is differentiated in embodiment, material, and energy level, thereby offering a view on how circularity theoretically can be embedded in engineering processes.

2.2. Model of SGE – System Generation Engineering

The model of SGE – System Generation Engineering [7] offers potential to support analysis and synthesis activities for planning circular development paths (2.1). The model of SGE serves as a description model and aims to support the description, planning and management of the development of systems and show interrelations between relevant systems such as the production or validation system [7]. The model is based on two fundamental hypotheses. First, each new system generation G_i is developed from a reference system R_i. This reference system consists of elements from existing or previously planned socio-technical systems and their documentation, which serve as the starting point for developing new generations. Second, the transition from R_i to a new system generation G_i can be described through three variation operators applied to reference system elements: carryover variation (CV), attribute variation (AV), and principle variation (PV) [7]: In a carryover variation, a subsystem from the reference system is retained with at most minor adjustments at interfaces. Attribute variation maintains the underlying solution principle but modifies its attributes at least partially. In line with Weber's understanding of characteristics and properties [13], both characteristics and properties can be captured through AV. Principle variation describes a change of the solution principle itself in order to fulfil the required function. The system under development next introduced to the market is represented as $G_{i=n}$, while the currently marketed generations are denoted as $G_{i=n-1}$ or previous generations as $G_{i=n-x}$ [7].

Within this work, a development path is understood as the temporally ordered sequence of (I) planned and realized states and (II) variations of a system across several generations. This perspective is consistent with strategic roadmapping approaches [14] and the notion of Albers [15], where even preliminary developments can serve as references for subsequent generations. In this work, a value-retention path denotes the degree of preservation, reflected by the potential level of value retention at which it occurs (i.e., system, subsystem, geometry, material or energy) [8].

2.3. Research Gap

The previous sections highlight that the model of SGE provides a promising foundation for describing and planning circularity in product engineering. However, existing approaches remain primarily theoretical and show limited practical applicability. In particular, we see potential for a model-based approach that systematically analyses circular development and value retention paths – retrospectively as well as prospectively. Furthermore, a specific description of variation operators that explicitly relates design changes to circularity targets is missing. Accordingly, there is a need for a formal description model that extends the model of SGE and furthermore sets the foundation for the prospective planning of new product generations with explicit consideration of circularity potentials.

3. Aim of Research, Research Questions and Methodology

3.1. Aim and Research Questions

The presented approach of Albers et al. [8] to integrate circular economy strategies into the model of SGE shows that there may be substantial interrelations between variations across system generations and circularity potential. Based on the preceding statements, the aim of this research effort is to present a formal description model based on the model of SGE to support the analysis of circularity potentials across system generations. The following research questions are answered for these reasons:

1. Which core factors are appropriate as a basis for assessing circularity potential and linking it to the model of SGE?
2. How can the model of SGE – System Generation Engineering be suitably extended to enable cross-generational analysis of circularity potentials?
3. To what extent is the proposed approach suitable for application to a mechatronic system?

3.2. Methodology

This research is structured according to the BLESSING and CHAKRABARTI'S Design Research Methodology (DRM) [16]. Figure 1 illustrates the study's methodological workflow mapped to the stages of the DRM.

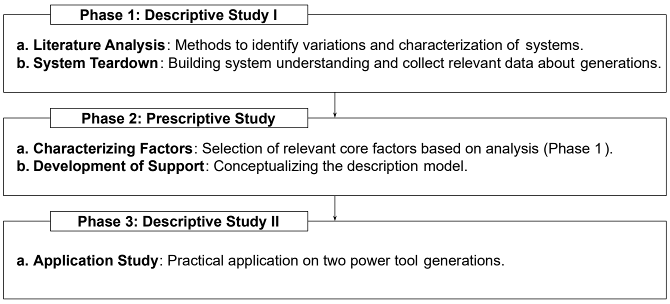

Fig. 1. Methodical phases of the paper.

Phase 1 (Descriptive Study I) consists of two elements: Firstly, a literature analysis on existing methods to identify variations and characterization of systems generations as well as circularity in product engineering is conducted. Further, a systematic teardown of three power tool generations is used to collect relevant data. The teardown leans on the procedural framework of TUSCH ET AL. [17]. *Phase 2* (Prescriptive Study) focuses on the prescription and synthesis for conceptualizing a methodical support to analyze variations across system generations. Lastly, the proposed approach is applied to two subsequent generations of a power tool (*Phase 3*).

4. Description Model for the Analysis of Variations across System Generations

4.1. Specifying Variations through Core Description Factors

To analyze variations and identify circularity potential systematically across generations, we consider both (I) the state of system characteristics (intra-generational) of the reference system, including associated reference system elements (e.g., previous product generations), and (II) the variation of product characteristics across generations (cross-generational). Based on that, RQ1 will be answered in this subsection.

Following Weber [13], developer-controlled design variables are termed characteristics. These characteristics largely determine a product's properties that cannot be set directly but emerge from the chosen characteristics [13]. In this work, we adopt this view: States of characteristics and their cross-generational variations are represented via a set of core factors *CF* (characteristics). These core factors can then be mapped to circularity-relevant factors (properties) – such as recyclability, detachability, or weight – and, where appropriate, to contextual criteria (e.g., regulatory requirements). Together with the proposed description model in section 4.2, this mapping of core factors with circularity factors aims to provide the foundation for a systematic analysis of circularity potentials within strategic product development. Cross-generational changes in the core factors serve as a specification of the SGE variation operators (CV/AV/PV). The proposed description model (sec. 4.2) captures these changes and forms the basis for linking and assessing circularity potentials. In this paper, we focus on analyzing the core factors to describe states and variations across generations.

Fig. 2 illustrates the relationship between the core factors (description layer) and circularity-relevant properties (assessment layer). Using this model, analysis activities aim to support identifying circularity potentials.

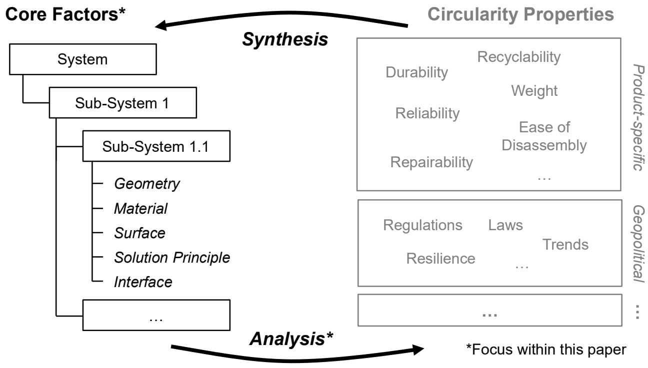

Fig. 2. Interrelation of core factors and circularity properties based on [13].

These core factors are derived from a synthesis of prior work by WEBER, TUSCH, and ALBERS et al. Following WEBER [13], products can be described by their structure, shape, dimensions, materials, and surfaces. As we integrate structure, shape and dimensions, we derive three core factors *geometry*, *material* and *surface*. *Geometry* comprises the shape, dimensions, and topology (i.e., the underlying internal mechanical structure). It also covers geometric tolerances, including form and position tolerances. *Material* captures the material types and specific grades. Choices at this factor drive a wide range of product properties. This can be mechanical (e.g., young's modulus, yield strength), environmental (e.g., life-cycle impacts) or economic (e.g., cost, manufacturing routes, provenance, recyclability). *Surface* captures both functional and aesthetic attributes. This includes roughness and waviness parameters, texture/topography (e.g., ground, polished, blasted), coating state (e.g., painted, galvanized, anodized), and visual characteristics such as matte/gloss finish, color patterns, and overall color scheme. *Solution principle* aligns with the model of SGE and captures how a function is technically realized – that means the physical effects or motions that produce the intended effect. It represents the fundamental solution or functional mechanism. Typical domains include mechanical (e.g., threaded joint, gear mesh, cylindrical press fit), electrical/electronic, magnetic, thermal, hydraulic, and related principles. *Interface* is defined as the portion of the design boundary that interacts with one or more other systems [17]. It describes how a subsystem is connected to or interacts with other subsystems (e.g., via joints or functional couplings). In our model, we explicitly capture interface changes across generations to evaluate cross-generational compatibility and, downstream, to inform the potential for non-destructive disassembly of the subsystem.

Building on these core factors, section 4.2 introduces the proposed notation of the description model to represent states and variations across system generations.

4.2. Extended Description Model

Based on the core factors identified in section 4.1, this chapter will answer RQ2 and present the extended model developed in phase II. The proposed description model in Fig. 3 builds on the model of SGE and considers a reference system $R_{i=n-1}$ together with its associated product generation $G_{i=n-1}$. Because this paper focuses on the retrospective analysis of variations between existing generations, we adopt the indexing *i=n-1*. The reference system R_i comprises internal references (e.g., earlier generations $G_{i=n-2}$, $G_{i=n-3}$, …) as well as external references (e.g., competitor products or cross-domain solutions). In view of material and structural carryover across generations, internal references are of primary interest. Beyond the illustrated pair of $R_{i=n-1}$ containing $G_{i=n-2}$ and $G_{i=n-3}$ the model can incorporate additional reference system elements and describe variations across two or more system generations both retrospectively and prospectively. Each product generation (system) is decomposed hierarchically into subsystems as follows:

$$System = \{S^a \mid a \in [1,k]\}, \qquad System = \{S^{a,b} \middle| b \in [1,l]\}$$

This decomposition recurses to deeper levels as required. By systematically comparing homologous subsystems across generations, we identify states and variations of core factors. Each variation is represented as a variation path $v(S)$ for subsystem S and characterized by the core factors defined in section 4.1. Within the model of SGE every cross-generational variation at system or subsystem level is classified by one of three variation operators: carryover (CV), attribute (AV), or principle variation (PV). The five core factors act as a specification of these operators by describing the transition of a reference system element into a subsequent or future generation (or its subsystems). In the proposed notation, a variation path v for subsystem S is defined as

$$v(Subsystem) = (XV; \{CF_f(x_{f,i=n-2} \rightarrow x_{f,i=n-1}; \Delta_f)\}.$$

The path is specified by the variation operator *XV* and the set of core factor *CF* transitions $\{x_{f,i=n-2} \rightarrow x_{f,i=n-1}\}$ denoting the states in the two generations. The associated change Δ_f describes changes quantitatively or qualitatively. We consider five core factors $f \in \{1,2,3,4,5\}$ and $XV \in \{CV, AV, PV\}$ introduced in sec. 4.1.

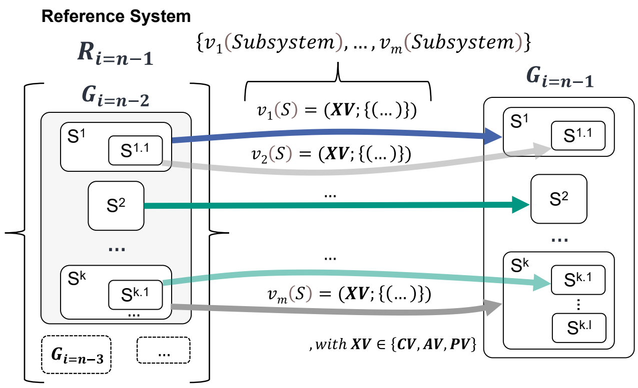

Fig. 3. Extended description model based on the model of SGE.

The proposed description model enables the systematic representation and analysis of variations and states across two or more system generations. The variation paths v(S) specified by core factor transitions serve as an assessment layer in which circularity-relevant properties are derived and aggregated into circularity potentials. Beyond analysis, the model aims to support prospective planning of circular development and preservation paths: by coupling context-specific circularity criteria to the core factors, alternative solutions of future generations may be synthesized model-based. This can be particularly valuable when new technologies emerge, as they may necessitate principle or attribute variations with significant core factor changes, potentially diminishing near-term circularity options. Using the model, such effects can potentially be identified early and future generations can be planned so that targeted subsystems undergo minimal change preserving compatibility and circularity potential.

In the following, we apply the extended model and systematically analyze the variations between two successive generations of an industrial power tool.

5. Case Study: Assessing Variations across Power Tool Generations

To answer RQ3, a first application of the description model (Section 4) was conducted on multiple generations of angle grinders. The products were disassembled via a structured teardown into subsystems. We then analyzed cross-generational variation for three representative subsystems – protective cover, bevel gear and drive unit. These subsystems illustrate three variation types of the model of SGE: carryover variation (CV), attribute variation (AV), and principle variation (PV). The variations are described via the core factors *CF* and formalized as variation paths $v(S)$ (see Fig. 4).

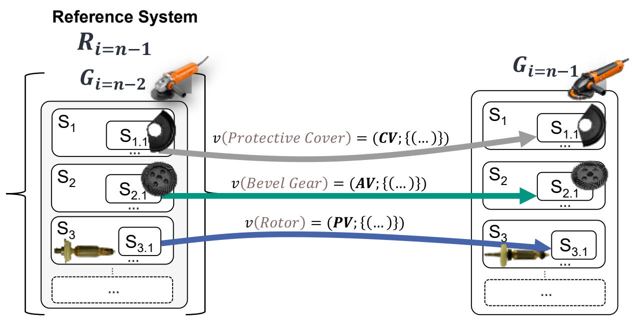

Fig. 4. Exemplary variation paths of two angle grinder generations (details below and in Table 1).

For the two investigated generations, the *protective cover* is identical; the subsystem is carried over unchanged. The interface is likewise unchanged, so no integration adaptations are required. This constitutes a special case of carryover variation (CV).

Accordingly, the variation path is

$$v(Pro.Cover) = (CV; \{CF_f(x_{f,i=n-2} \rightarrow x_{f,i=n-1}; \Delta_f = 0)\})$$

with no variation in core-factors $\Delta_f = 0$.

The *bevel gear* shows a different pattern. The core factors *CF* geometry and surface differ between generations, whereas material, interface, and the solution principle remain unchanged. This is consistent with retaining the mechanical torque-transmission principle; accordingly, the change is classified as attribute variation (AV) with $\Delta_{geometry} \neq 0$, $\Delta_{surface} \neq 0$, $\Delta_{material} = 0$, $\Delta_{principle} = 0$ and $\Delta_{interface} = 0$. The states and variation of the core factors are shown in Table 1 and describe the respective variation path *v*:

$$v(Bevel\ Gear) = (AV; \{CF_f(x_{f,i=n-2} \rightarrow x_{f,i=n-1}; \{\Delta_g, \Delta_m, \Delta_s, \Delta_i, \Delta_p\})\})$$

In subsystem S_3 (*drive unit*), several components exhibit distinct variation paths (e.g., bearings, impeller, plastic cap, bevel gear, rotor, shaft). We focus on S3.1 – rotor (armature + shaft), which shows a principle variation (*XV* = PV): the DC motor is replaced by a permanent-magnet synchronous motor. Accordingly, the armature – previously composed of laminations, windings and a commutator – transitions to laminations with permanent magnets. This implies *XV* = PV with a change of the solutions principle $\Delta_{principle}$, typically accompanied by substantial core factor variations in geometry/material/surface on subsystem level [7].

This case illustrates that a principle variation (PV) can occur at system level. However, at lower hierarchical levels (subsystem), the change may decompose into attribute variations (AV) and carryover variations (CV) with smaller core factor deltas.

From the observed variation paths in combination with the core factors, we can deduce that potential value-retention paths may occur either at the structural level (reuse, refurbishment, remanufacture of subsystems) or – if this is not feasible – at material level (recycling). In the special case of a discontinued subsystem (i.e., a reference-system element without a successor in the next generation), material-level recovery may be the only viable option (e.g., the metal plate ahead of the impeller ring in subsystem S3). Wear parts constitute another special case. Assuming the bevel gear is subject to wear, high structural recoverability and compatibility with the successor generation are expected to require additive and/or subtractive reprocessing (e.g., re-toothing, minor geometry adaptations). In such cases, a targeted design of the material core factor can be advantageous, whereas small geometry changes alone are likely to contribute less to circular leverage.

Table 1. Core factors states and variations of the bevel gear.

δCore-Factor	$X_{f,\,i=n-2}$		$X_{f,\,i=n-1}$	Δ_f
δGeometry:	Ø51,3x14 [mm]	→	Ø51,1x17 [mm]	$\Delta_{geometry}$: Gear thickness
δMaterial:	25CrMo4	→	25CrMo4	$\Delta_{material}$: 0
δSurface:	Sintered surface, re-milled teeth, matte light	→	Lathed finish, re-milled teeth, matte dark	$\Delta_{surface}$: Surface structure
δInterface:	CPF, tooth flank contact	→	CPF, tooth flank contact	$\Delta_{interface}$: 0
δSolution Principle:	Mechanical: spiral toothed	→	Mechanical: spiral toothed	$\Delta_{principle}$: 0

Further, the model emphasizes that development paths in the sense of the model of SGE (CV, AV, PV) do not necessarily coincide with feasible value retention paths. This is particularly true for wear parts that require reprocessing even if a CV case exists or for components whose material changes between generations (AV). In the latter case, an AV may describe the development path but initially does not imply a direct value-retention path – similar to the illustrated case of the metal plate in drive unit S_3. Although a material change ($\Delta_m \neq 0$) directly influences the circularity strategy and value-retention paths, the new generation may still perform better in terms of cost and environmental impact. In other words, cross-generational variation typically reduces near-term circularity potential (because direct carryover is impeded), yet the same change can improve the circularity potential of new generations by enabling closing material loops on higher value levels. Here, the proposed description model with its core factors and variation paths become useful: They capture the states of both generations and provide the basis for a subsequent circularity assessment based on variations and state transition itself. •

Finally, although we applied the model retrospectively in this study, we see potential that this notation supports prospective synthesis. In future research, alternative core factor states and variation paths v(s) for $G_{i=n}$ as well as future generations $G_{i=n+1}$ and $G_{i=n+2}$ can be explored to enable planning of circular development and value-retention paths.

6. Conclusion and Discussion

This paper introduced a formal description model extending the model of SGE to capture states and cross-generational variations through five core factors *CF* and to represent these changes as variation paths v of a subsystem *S* of a respective reference system R_i. The description model provides a structured way to analyze variations across system generations and establishes the basis for linking variations to circularity-relevant properties in subsequent assessment steps. The case study on two generations of an angle grinder demonstrated the practical applicability of the model and showcases the three variation types in practice: carryover variation (CV) for the protective cover, attribute variation (AV) for the bevel gear, and principle variation (PV) for the drive unit. The model emphasized the conceptual distinction between intra-generational states and cross-generational variations. While cross-generational variations of core factors tend to impede direct carryover in the near term and therefore impact circularity potential, changed core factor states may improve cost and environmental performance for a single generation.

Moreover, core factor transitions may enable value-retention paths at higher value levels in future generations. The extended description model captures these states and transitions and thereby supports retrospective analysis of variations across system generations. Furthermore, by formalizing states and variations, the model provides a basis for prospective planning of development and value-retention paths to improve circularity of future generations.

Limitations are that the core factors constitute an accessible, manageable description on a strategic level rather than a holistic product description. This is intentional, as the model targets cross-generational reasoning and early-phase decision-making rather than detailed embodiment modelling. Consequently, the core factors enable systematic comparison across generations but do not aim to capture the full product definition. Also, scalability and normalization of factor transitions, as well as transferability beyond the power tool domain, require further investigation. The model explicitly targets circularity strategies that depend on product-design decisions in the technical cycle (reuse, repair, refurbishment, remanufacturing, recycling); strategies not requiring product development activities lie outside the scope of this work. Finally, although circularity is commonly regarded as a pathway toward reduced resource consumption, it does not automatically imply overall sustainability. While quantitative supply-demand balancing across generations is beyond the scope of this work, the description model delivers structured information on cross-generational development paths that can support such analyses.

Future research should integrate the representation of states and variations of core factors with quantitative circularity metrics to enable systematic evaluation. Model-based systems engineering may further enhance consistency, traceability and applicability. Linking the model with strategic product planning and roadmapping will be essential to operationalize the planning of variation paths for $G_{i=n}$ and future generations $G_{i=n+1}$, $G_{i=n+2}$. This integrated consideration has the potential to transform the model into a forward-looking approach for guiding circular system generation engineering in the context of strategic product development.

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