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Procedia CIRP 140 (2026) 683–688

www.elsevier.com/locate/procedia

33rd CIRP Conference on Life Cycle Engineering (LCE 2026)

Towards a Reference Architecture Model for the Perpetual Innovative Product

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Abstract

In view of shrinking resources, stricter climate targets, and rising customer expectations, circular product development is a key lever for decoupling economic growth from raw-material consumption. At the same time, the innovation potential in product engineering must be maintained at an adequate level. Although initial concepts exist, processes and methods that integrate product modeling, architecture analysis and cross generational circularity strategies are still lacking. This study proposes a systematic analysis procedure to support the development of a reference architecture model for circular system generations. The analysis activities are initially applied on three generations of a mechatronic system from the power tool domain. After a systematic teardown, the subsystems of each generation are mapped to the property, function and physical structure view, resulting in three instantiated product models. These models are then analyzed to show common and varying elements and to reveal how structural changes propagate across generations. The resulting artefacts provide a systematic approach as a basis for developing a system-specific reference model that can support future circular design decisions and the planning of circular system generations.

Keywords: Product Development; Design Methods; Product Architecture; Circular Economy; Circular Product Development

1. Motivation

Circular product development is recognized as a key strategy for decoupling economic growth from resource consumption while preserving competitiveness [1]. Despite this, the potential of secondary materials remains significantly underutilized [2], [3]. Common eco-efficiency initiatives pursue the goal of “doing more with less”, yet are considered reactive and continue to operate within linear value creation models [4]. The hesitation to adopt circular approaches is amplified by limited market acceptance and manufacturers’ fears of cannibalizing primary markets, while simultaneously, increasing consumer demand, accelerating technology and product life cycles increase the pressure to innovate [3], [5].

The *Collaborative Research Centre (CRC) 1574 Circular Factory* investigates the emergence of the Perpetual Innovative Product (PIP) – a vision of a product that, through maximal value-retention, minimal disassembly of older generations and targeted technological updating, achieves the same innovation potential and quality as linearly manufactured products [6]. Through cross-generational circularity in product development, product instances and their subsystems are continuously transferred into new product generations, thereby enabling perpetual product use [7]. In product engineering, the development of the PIP can be supported by a reference model,

10.1016/j.procir.2026.05.115

including an adaptive architecture, grounded in multiple sources of knowledge and enabling the planning and development of alternative solutions for circular product generations [7]. This, in turn, requires analysis activities that directly contribute to and populate such a model. In other words, the reference architecture model is supposed to act as a methodical support for circular design decisions across generations, aligning value-retention and circularity options with product development early on.

The aim of this paper is to identify and structure analysis activities that provide a methodological basis for developing a system-specific reference model for the PIP. Based on existing literature and practical investigations, we exploratorily derive a systematic analysis approach that supports the cross-generational description of product generations in terms of their properties, functions, and physical structures. Furthermore, we examine the initial applicability of the procedure in a case study and generate artefacts such as instantiated product models and cross-generational variation patterns. The resulting artefacts are intended to lay the groundwork for future synthesis and consolidation into a reference model for circular product engineering.

2. Related Work

The circular economy aims to decouple value creation from primary resource use by keeping products, their subsystems and materials in technical cycles [1]. In product engineering, this requires early design and architecture decisions that support technical loops such as reuse, remanufacturing and recycling [8], [9]. Strategies include 'Design for X'-methods such as design for (dis-)assembly, standardization or modular, upgradable architectures that facilitate maintenance, reuse and high value-retention paths [8], [10]. While frameworks such as the R-strategies provide a taxonomy of circularity options [11], their operationalization in engineering practice emphasizes mainly single product generations [12]. There are approaches to circularity-oriented product architecture design, but they mostly focus on the physical structure and modularization strategies within one generation [13]. Beyond the physical structure of the generation under development, subsequent generations, future needs and the associated production system must also be considered, given the coexistence of linear and circular production [7].

The Model of SGE – System Generation Engineering serves as a description model that supports the description, planning, and management of the development of new systems [14]. It offers potential to underpin analysis and synthesis for circular product engineering [12]. The model of SGE rests on two core hypotheses: (1) Every new system generation G_i is derived from a reference system R_i, i.e., a set of elements drawn from existing or previously planned socio-technical systems that serve as the starting point for developing new generations. (2) The transition from R_i to G_i can be expressed through three variation operators applied to reference-system elements: carryover variation (CV), attribute variation (AV), and principle variation (PV) [14]. In CV, a subsystem is retained with at most minor interface adjustments; AV preserves the solution principle but modifies its attributes – capturing both characteristics and properties in the sense of [15]. PV changes the solution principle itself to fulfil the required function. The system generation currently under development and next to be introduced to the market is denoted $G_{i=n}$, while generations already on the market are $G_{i=n-1}$ and earlier ones $G_{i=n-x}$ [14].

Albers et al. [16] classify system models along two dimensions in a systematic framework: the level of instantiation and the degree of individualization [16]. At one end, meta models provide highly generic and domain-independent descriptions, while at the other, real systems represent fully instantiated and individualized products. Between these, reference system models capture reusable knowledge and structures across generations, serving as templates for developing system models of specific products [16]. To describe different viewpoints on system development in the context of SGE, the generic reference system model was introduced [17]. The system view is partitioned into three perspectives: the property view, the function view, and the physical view [17]. The property view comprises solution-open product properties that can be perceived by the customer. These properties can be made concrete via product functions in the function view. The product functions and subfunctions, in turn, can be realized by solution-specific subsystems that are represented in the physical view [17]. For the property view, Characteristics-Properties-Modelling (CPM) can be used [15]. CPM distinguishes characteristics (design/structural parameters under developer control) from properties (resulting behavior). It supports both analysis – deriving or predicting properties from given characteristics – and synthesis – selecting characteristics to achieve required properties [15]. The approach is considered suitable since SGE variations can be applied to both characteristics and properties [14]. For the function view, function-modelling of the Product Architecture Design Methodology approach can be applied [18], [19]: First, the overall system function as a black box with inputs and outputs is captured. In a next step, this flow is decomposed into subfunctions that transform inputs to outputs. Finally, these function chains are networked and refined to obtain the function structure of the system [18]. An earlier approach combining the generic reference product model and function modelling was demonstrated in [19] for the cross-generational planning of upgrades.

Existing work offers approaches for modelling products, for architecture analysis and for circular product design. However, a structured procedure that systematically links these approaches to derive actionable inputs for developing a circular reference architecture model remains missing. In particular, methods that enable a structured, cross-generational description of products – capturing their properties, functions and physical structures – have not been yet aligned to support the long-term goals of circular product engineering. This paper addresses this gap by focusing on the identification and structuring of such analysis activities as a methodological basis for future synthesis and consolidation into a reference product model that enables cross-generational value-retention.

3. Aim of Research, Research Questions and Methodology

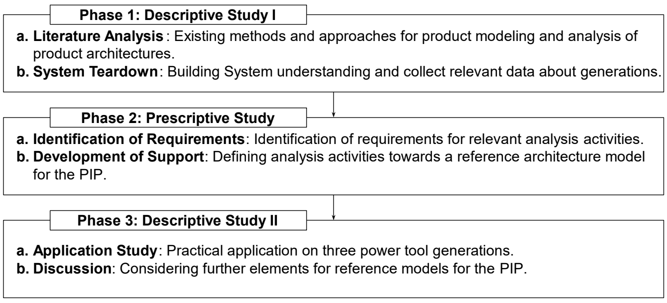
3.1. Aim and Research Questions

As argued above and motivated by [7], reference models and architectures are promising levers towards the development of the PIP. This paper aims to identify relevant analysis activities that support the development of a reference architecture model. We elicit requirements for such analysis activities and propose a systematic analysis procedure accordingly. To achieve this aim, we address the following research questions:

1. What requirements for analysis activities arise when developing a reference architecture model for the PIP?
2. Which analysis activities constitute a suitable systematic procedure?
3. What are opportunities and challenges of the proposed approach?

3.2. Methodology

This research is structured according to the Design Research Methodology (DRM) [20]. Fig. 1 illustrates the study's methodological workflow mapped to the stages of the DRM.



Phase 1: Descriptive Study I

a. Literature Analysis: Existing methods and approaches for product modeling and analysis of product architectures.

b. System Teardown: Building System understanding and collect relevant data about generations.

Phase 2: Prescriptive Study

a. Identification of Requirements: Identification of requirements for relevant analysis activities.

b. Development of Support: Defining analysis activities towards a reference architecture model for the PIP.

Phase 3: Descriptive Study II

a. Application Study: Practical application on three power tool generations.

b. Discussion: Considering further elements for reference models for the PIP.

Fig. 1. Methodological steps of the study.

First, a literature analysis of existing approaches in product modelling and product architecture is conducted. In the next phase, a system teardown is performed as a preparatory step (Phase 1). From DSI, requirements for analysis activities are identified. Based on these requirements, a systematic procedure towards a system-specific reference architecture model is derived (Phase 2). Finally, the procedure is applied to three generations in DSII to evaluate requirement fulfilment and discuss further elements for a reference model for the PIP (Phase 3).

4. Deriving a Systematic Analysis Procedure toward a Reference Architecture Model for the PIP

4.1. Requirements for a System-Specific Reference Architecture Model

This chapter addresses RQ1 by identifying requirements for analysis activities. Starting from the hypothesis that new system generations are developed from a reference system and that a Perpetual Innovative Product (PIP) is enabled by continuously transferring subsystems from older into the latest generation, a cross-generational perspective is required. The generic reference product model introduced in section 2 leverages the model of SGE and serves for the specification of system generations. Given the need to integrate best practices and further influencing factors on product architecture – e.g., future user, customer and provider needs or production-system constraints – the partition into solution-open properties, functions and solution-specific physical structure is considered useful. This tri-layer structure is also where circularity touchpoints can be specifically linked and managed. The identification of analysis activities is aligned with the abstraction levels of system modelling according to [16]. As indicated in Fig. 2, there are two activities required towards a system-specific reference model within the framework: First, the system and therefore the content of the model needs to be specified through individualization (Generic reference product model (A2) to a system-specific level (C)). Second, an inductive procedure is required to derive a reference model from real products.

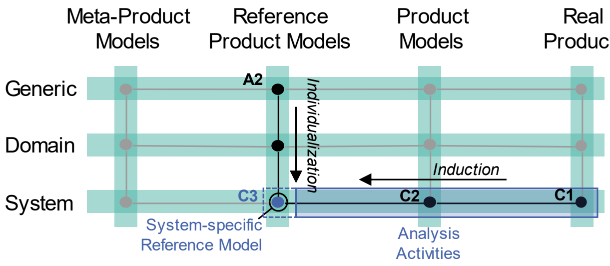


Fig. 2. Analysis along the abstraction levels of system modeling [16].

This necessitates the establishment of system-specific understanding, which should be ensured by conducting analysis activities and applying them to real products (C1). To derive instantiated product models (C2) from real products and to map them into the structure of the reference product model, analysis of the product and functional structure and the system properties are required. Finally, together with the resulting specifications of references as instantiated product models (C2), the cross-generational changes and relations provide the input and knowledge base for the intended system-specific reference product model (C3).

4.2. Systematic Analysis Procedure

Based on the identified requirements in section 4.1, a systematic analysis procedure is derived to answer RQ2. The analysis activities are shown in Fig. 3. It comprises three overarching steps – *System Analysis* (I), *Instantiated Product Modelling* (II) and *Cross-Generational Analysis* (III). The steps are detailed in the following sections.

4.2.1. System Analysis

As the initial analysis activity, *System Analysis* (I) builds understanding of the investigated system and captures relevant data. It draws on the differential analysis procedure by [21]. The activity comprises the steps *Planning*, *Preparation*, *Decomposition*, and *Analysis*; the latter is executed in a modified form with a focus on architecture and properties in subsequent steps. In *Planning*, the system generations (C1) to be investigated are selected. The selection depends on the intended abstraction level and the objective of the reference model. In *Preparation*, the teardown and analysis are set up, including the definition of a uniform disassembly depth, the specification of functional groups and the preparation of the data-collection format with suitable documentation conventions for system levels. In *Decomposition*, the selected systems are dismantled and data is recorded to serve as input for subsequent steps. Particular attention is paid to interfaces, connection types or disassembly accessibility as future levers for circularity options.

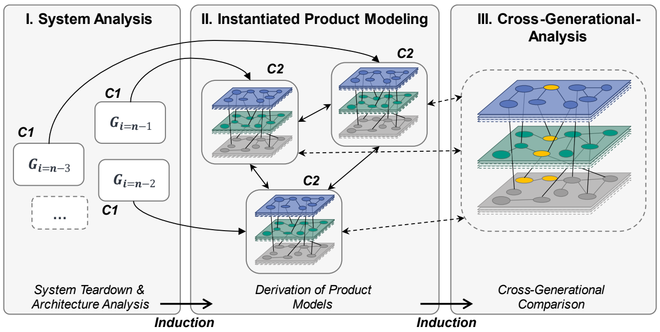


Fig. 3. Overarching analysis activities towards a reference model.

4.2.2. Instantiated Product Modeling

In order to develop a potential reference model (C3) for the PIP, the given system generations (C1) need to be compared and analyzed. Therefore, instantiated product models (C2) for each generation are derived. This follows the core idea of the PIP: Transferring product substance from past generations into new ones. Modelling is aligned with the reference model introduced in section 2 and its three perspectives: properties, functions and physical structure. For the property view, we adopt the CPM approach introduced in section 2. Based on known characteristics of the selected systems C1, properties can be determined. Characteristics of C1 are obtained via tests and measurements, from which properties are derived. Alternatively, manufacturer data are used where appropriate. The functional view is derived using the procedure by [18]. First, the system's overall function is captured and modelled as a black box with defined inputs and outputs. Next, subordinate function chains are formed to describe the transformation from inputs to outputs. Finally, these chains are networked into a functional structure. To complete the instantiated models, the physical structure is captured by using data from *System Analysis* (I). First, the documentation of the system architecture is completed on an overall system level, then, if necessary, the relevant subsystems are modeled in detail. The outcome is a set of instantiated product models explicitly describing properties, functions, and physical structure. These models are transferred as reference system elements into a reference model for the PIP and provide the basis for subsequent analysis and synthesis activities.

4.2.3. Cross-Generational Analysis

In analysis step III, the instantiated product models are examined across generations. First, interactions between the three views (properties, functions, physical structure) are made transparent; second, changes over generations are identified. The integrated consideration of both aspects exposes intra- and inter-generational dependencies and helps to identify critical elements for a future reference model – e.g., subsystems with many interfaces.

Table 1. Intragenerational combined DMM and DSM structural analysis.

	Properties P	Functions F	Subsystems S
Properties P	P-P	P-F	P-S
Functions F		F-F	F-S
Subsystems S			S-S

To analyze the logical architecture and its relations to properties, we apply Multiple-Domain Matrices (MDM) to the product models [22]. The MDM combines Design Structure Matrices (DSM) and Domain Mapping Matrices (DMM). As shown in Table 1, one MDM per product model C2 comprises three DSMs (P-P, F-F, S-S) and three DMMs (P-F, P-S, F-S). Through DSM, intra-domain relations among individual properties, functions and subsystems are identified. DMM capture the inter-domain relations between the three product-model layers. The identified intra- and inter-domain relations constitute the structural basis for synthesizing a reference architecture by enabling an understanding of how variations propagate across the system. After mapping interactions between the views, cross-generational differences for properties P_i, functions F_i und subsystems S_i are determined. For each transition across generations, elements are classified as removed, carryover, modified or added (Table 3). The classification follows [23] and can be linked to the variation operators of the model of SGE.

Table 2. Cross-generational analysis (removed, unchanged, modified, added).

	$G_{i=n-2} \rightarrow G_{i=n-1}$	$G_{i=n-1} \rightarrow G_{i=n}$	$G_{i=n} \rightarrow G_{i=n+1}$
Properties P^i		remove, carryover, modify, add	
Functions F^i			
Subsystems S^i			

This cross-generational analysis makes changes between systems observable. In conjunction with the preceding structural analyses, it highlights the implications of changes, supporting both retrospective compatibility checks of older generations and prospective examination of potential changes in future generations to support circularity assessments and development decisions.

5. Application of the proposed Approach

5.1. Tear Down and Analysis of the System

The procedure was piloted on three successive generations of compact-class angle grinders (C1). While the full teardown dataset covers all subsystems of the three product generations, one subsystem is used illustratively in section 5.3. In *Planning*, we selected three consecutive generations from this class. In *Preparation*, we specified a complete teardown wherever feasible non-destructively with available tools. We defined the following functional groups: drive, housing, operator interface, electrics, cooling and safety. The documentation schema comprised: disassembly level, disassembly friendliness, functional group, dimensions, mass, and material. All interfaces and types of connection were recorded. In *Decomposition*, the systems were dismantled and documented.

5.2. Deriving Instantiated Product Models

In this step, instantiated product models were created for each of the three generations based on the investigated products (C1). First, using the CPM approach, the relevant properties of each system were captured. The required data were taken either from manufacturer specifications or recorded during the teardown and system analysis (sec. 5.1). Building on the identified properties, the functional structure was elaborated.

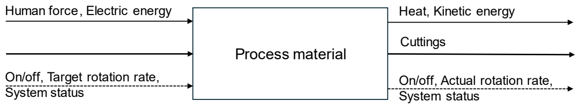


Fig. 4. Overall system function modelled as black box.

As outlined in section 4.2, we began with the overall system function modelled as a black box (Fig. 4). From this, function chains were derived, subsequently networked and refined as needed. To complete the instantiated product models, the physical structure of the systems was documented based on the data from section 5.1 and the system understanding gained through the teardown.

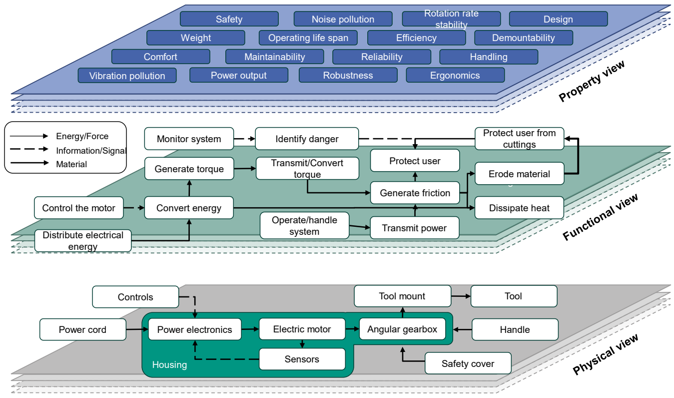


Fig. 5. Instantiated product model of the newest investigated angle grinder.

The outcome of this step is a set of instantiated product models for all three generations, each comprising properties, functions and physical structure. A simplified view of the model for the newest system generation is shown in Fig. 5.

5.3. Identifying Cross-generational Differences

As outlined in section 4.3, we first established the cross-domain relations between the three layers of the product models. The analysis indicates a partially modular architecture consisting of power electronics, drive unit and output unit. In a second step, we classified cross-generational changes for selected elements. Table 4 illustrates the pattern for the electric motor (part of the drive unit): several properties (e.g., input power, output power, efficiency, weight, robustness) alternate between carryover and modified across generations; functions like "determine position" and "dust protection" were added from $G_{i=n-2}$ to $G_{i=n-1}$ and due to a different drive technology "Reverse current direction" was removed; the subsystem "electric motor" itself is modified in both transitions. Due to the motor's strong interrelations within the systems, even minor changes on subsystem level can have an impact into the surrounding physical structure.

Table 3. Cross-generational differences on the example of the drive unit.

	$G_{i=n-3} \rightarrow G_{i=n-2}$	$G_{i=n-2} \rightarrow G_{i=n-1}$
E^1: Input Power	modified	carryover
E^2: Output Power	modified	modified
E^3: Efficiency	carryover	modified
E^4: Weight	carryover	modified
E^5: Robustness	carryover	modified
F^1: Reverse current direction	carryover	removed
F^2: Determine position	-	added
F^3: Protect from dust	-	added
S_1: Electric Motor	modified	modified

These changes at subsystem level also affect the resulting properties, while functional changes are not necessarily required and depend on the extent of the physical modification. These observations illustrate how variations across generations can indicate where a reference architecture should stabilize interfaces and where it should allow planned variability to support technological updates. The approach thus contributes to circular product engineering by making explicit how variations in properties and functions propagate into the physical architecture and, in turn, influence potential value-retention paths such as remanufacturing, upgrading or recycling. By linking these effects within and across generations, the approach provides a coherent analytical basis for a future reference architecture that supports targeted design decisions aimed at maximizing circularity and value-retention potential. This basis enables a system-specific reference architecture model that integrates not only physical design aspects but also technological, production-related and contextual influences across the tri-layer structure.

6. Discussion and Outlook

This work identified and linked analysis activities from existing literature and structured them into a systematic procedure to support the development of a reference architecture model for circular product generations and the vision of the PIP. To answer RQ1, we elicited requirements (cross-generational perspective, inductive approach, solution-open and -specific product views). We then organized the analysis into three overarching steps (RQ2): *System Analysis* (I), *Instantiated Product Modelling* (II) and *Cross-Generational Analysis* (III). In the DSII, we applied the procedure initially to three successive system generations (RQ3). The procedure was qualitatively validated through its application to three successive product generations; future research will extend this validation through quantitative evaluation and industrial feedback. While this work does not yet instantiate the reference architecture itself, it provides the analytical framework and key artefacts that constitute the foundation for synthesizing a system-specific reference model in subsequent research. Unlike conventional approaches that focus solely on the physical level or lack a cross-generational perspective, the proposed procedure establishes a foundation to integrate additional factors relevant to the PIP – such as production-related constraints, evolving technologies and contextual influences – into a reference model for circular product generations.

While the procedure provides actionable insights into system properties and architecture, synthesis steps for deriving new, circular system generations remains a future step. To advance from analysis to synthesis, the derived artefacts – instantiated models and variation patterns – must be consolidated into a system-specific reference architecture. Future needs and benefits (customer, user, provider) as well as context factors (social, technological, economic) should be integrated to ensure that the development of new generations is forward-looking and achieves high innovation potential while maintaining circularity potential. This can be achieved by linking the analysis artefacts with foresight methods and product-profile modelling to anticipate future properties and support development decisions. A reference model should also, through integrated consideration of product and production (Product-Production-CoDesign), support cross-generational planning of compatibilities as well as required production capacities and capabilities. Given the diversity of influencing factors, Model-Based Systems Engineering (MBSE) can support modeling these relations, manage complexity and maintains consistency across model layers and generations.

In summary, the proposed analysis procedure provides a methodological foundation for developing a system-specific reference model that provides the basis for linking intra- and cross-generational insights on product architectures and value-retention paths. This analytical basis supports future integration of technological, production-related and contextual influences – advancing the development of circular product generations and the vision of the Perpetual Innovative Product.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1574 – 471687386

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