Bringing the Vision of Perpetual Innovative Products to Life - challenges and opportunities at the circular factory for angle grinders

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Abstract

In the circular economy, the contradiction between developing innovative products and reusing products from the market is a huge challenge. On the one hand, products returned from the market are, by design, unable to meet the requirements and functions of the newest product generation, hindering innovation in circularity. On the other hand, retaining the product's added value is a powerful lever for enabling sustainable circularity. Perpetual innovative products could solve this contradiction. However, the problem is that up to now it remains

mostly a vision. This vision needs to address three key challenges to come to life: analyzing used products and subsystems, predicting functionality at the individual level, and reprocessing subsystems in a way that enables them to fulfill the newest functions. In this paper, we illustrate the collaborative approach to address these challenges. We structure insights and the challenges encountered in various solutions for implementing this vision, using the example of a circular factory for angle grinders. From incorporating asymmetrical degradation into product specifications to measuring strategies and reprocessing parameters, this paper shows how a vision can come to life. The uncovered insights and difficulties reveal opportunities for further development and interdisciplinary research in circular factories.

Keywords: Circular Economy, Circular Factory, Functional Modeling, Product-Production CoDesign

1 Introduction

The transition to circular economy is driven by various challenges e.g. overconsumption of resources on a global scale, resource scarcity or geopolitical trade disruptions [1]. Barriers for circular economy can be clustered in policy, technology and public participation [2]. A central challenge posed by technology is the tension between developing innovative products and reusing products on the market. On the one hand, products returned from the market are, by design, unable to meet the requirements and functions of the newest product generation, hindering innovation in circularity [3]. On the other hand, retaining the product's added value is a powerful lever for enabling sustainable circularity.

Perpetual innovative products could solve this contradiction [4] However, the problem is that up to now it remains mostly a vision. This vision needs to address certain challenges to come to life: analyzing used products and subsystems, predicting functionality at the individual level and reprocessing subsystems as well as a design for circularity that enables products from the circular factory to fulfill the newest functions. This paper investigates challenges and upcoming opportunities from previous works on circular factories following the research question: *Which challenges and opportunities emerge in product analysis, reprocessing, and design in a circular factory for perpetual innovative products?*

2 Methodology

In the following section, the circular factory for perpetual innovative products and identified key challenges from previous work as basis for this case study are presented, followed by the case study setup.

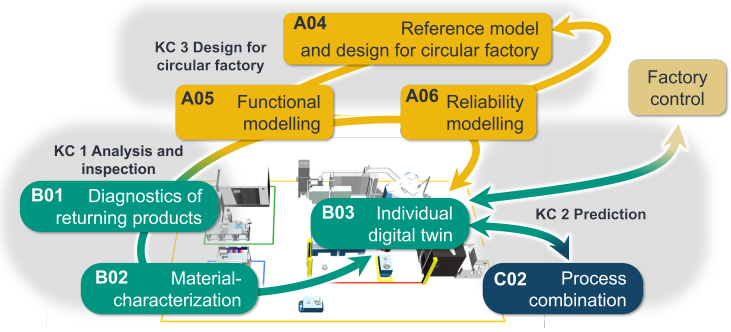


Fig. 1 Structure of the research topics and assigned sub-projects of the CRC

2.1 The circular factory for perpetual innovative products

In the circular factory for perpetual innovative products, linear and circular production principles are combined to manufacture products that meet the latest functions and fully satisfy customer needs in the primary market. It follows the principle of using as many of the "old" subsystems and components in these products as possible and integrates linear production where the functional requirements cannot be met by circular production. [3]

2.2 Research team in the case study

Based on these three key challenges, approaches implemented in the collaborative research center CRC 1574 "circular factory for the perpetual innovative product" are described and discussed in a case study of the circular factory for angle grinders. Participants in the case study were 21 researchers: 8 professors, 2 postdoctoral researchers, and 11 doctoral researchers, organized into 7 sub-projects assigned to specific research fields necessary to address the key challenges. To interconnect the research addressing the key challenges, monthly workshops with presentations and discussion rounds were held. Here, research activities were initiated, progressed and presented to the group. An overview of the key topics of the sub-projects and the addressed challenges is given in Fig. 1

2.3 Key challenges from the product's perspective

2.3.1 KC 1: Analysis and inspection of used products and subsystems

This key challenge stems from the unknown and individually worn-down state of products and their components when they return from the market. To use them as a basis for "new" products, the characteristics of their embodiment need to be known at the individual level, considering geometrical and material challenges that lead to wear [5]. Identifying these characteristic requires suitable and adaptive measurement technology in the inspection station of the circular factory [6]. This key challenge is

addressed by collaborations between the sub-projects A05, A06, B01, B02, and B03 (see Fig.1)

2.3.2 KC2: Prediction for pairing and reprocess of the embodiment

Often, the worn-down components entering the circular factory are not directly usable for manufacturing "new" products. They need to be combined based on individual characteristics (pairing approaches, e.g. [7]) or reprocessed. This reprocessing requires high flexibility, and additive approaches are often necessary to modify characteristics in ways that overcome geometric or material wear. This key challenge is addressed by collaborations between all sub-projects with the focus on A06 and C02 as the sub-projects are strongly related to development and production of the "new" products from the circular factory

2.3.3 KC3: Design for Circular Factory

Design for Circular Factory supports product engineering by addressing how product generations can be developed to enable the cross-generational integration, reprocessing, and technological updating of subsystems and components from previous generations while fulfilling the requirements of future product generations. The key challenge is developing a design approach that integrates continuous cross-generational technological updates, maximizing the possible reuse potential with a reference product architecture. This necessitates a cross-generational perspective to assess subsystem suitability for feasible future value-retention paths. Therefore, previous, current, and future product generations and production systems are interconnected through a common development path, enabling decision-making for cross-generational design changes of the Perpetual Innovative Product. [8]

3 Case study circular factory for angle grinders

In the following, the approaches and results from the collaborative sub-project efforts regarding the key challenges are described.

3.1 KC1 Analysis and inspection of used products and subsystems

The inspection in the circular factory requires an overfit of sensor technologies to inspect the dimensions of functional behaviour and geometric embodiment including surface defects like pitting or cracks with required confidence. The inspection process including modelling of uncertainties is shown in Fig. 2 The implemented measurement strategies including functional test benches and CT scan enable minimal invasive inspection on subsystem and component level, as no unnecessary disassembly is needed. Often, an individualized multi-sensory approach is needed to capture specific phenomena needed in subsequent functional modelling. Here, also decomposition of embodiment into measurable characteristics becomes a prerequisite for tractable reprocessing decisions. A three-way distinction into design, manufacturing and degradation is needed to describe the products embodiment and identify their relation

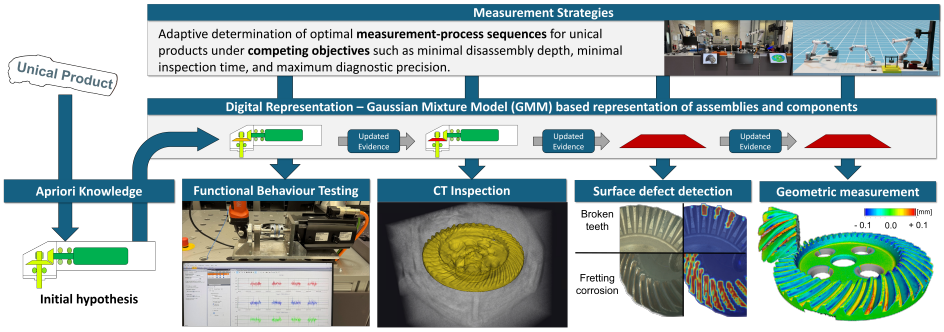


Fig. 2 Overview of the inspection process in the circular factory, using measurement strategies to update digital representations of the product to identify the embodiment [9].

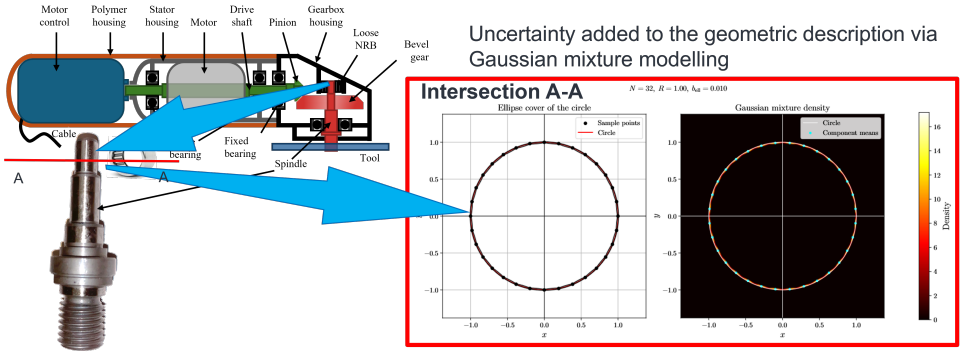


Fig. 3 Uncertainty added to the Computer-aided design (CAD) model showing the diameter at the needle bearing seat of the spindle shaft as example

to functional behaviour. In subsequent reliability modelling, diagnostic variables are structured into current system state, recent usage history, and degradation-related health indicators. [10, 11] To provide embodiment data for circular factory decision making, the CAD model is enriched with uncertainty using Gaussian mixture modelling (see Fig. 3) In this way, uncertainty is incorporated directly at the geometric level rather than being added later as an external heuristic. This enables the CAD systems to maintain interpretable local structure while also supporting probabilistic reasoning. This supports the needed tolerance-aware geometric analysis, uncertainty-aware digital twins, robust registration, probabilistic collision checking, and geometry comparison under imperfect knowledge.

Remaining and emerging challenges regarding KC1 are the profound measurement systems needed to identify changes inside tolerance fields defined for linear manufacturing as in circular production, the initial manufacturing process can't be controlled anymore. Also irregular wear resists generic characteristic definitions and requires instance-specific approaches.

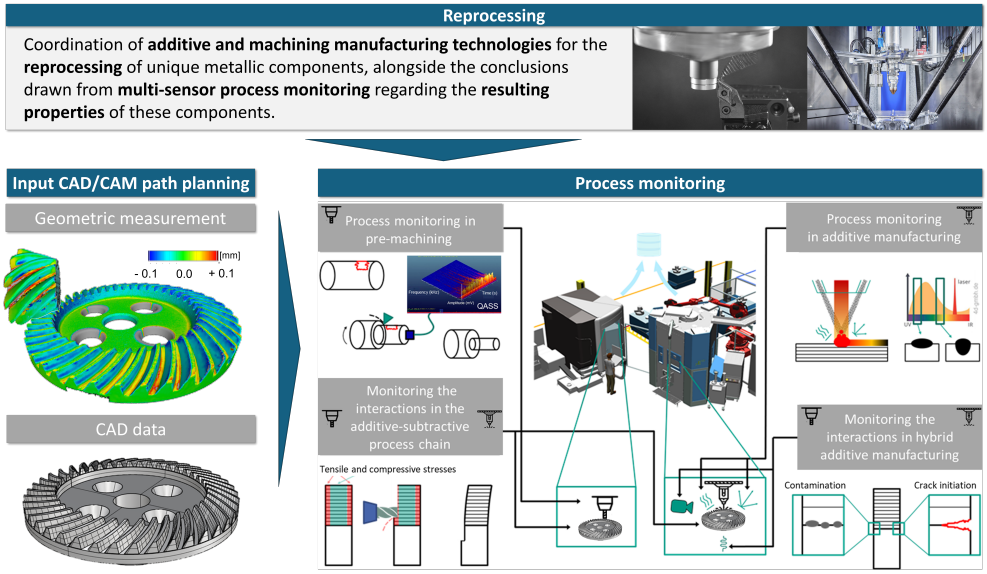


Fig. 4 Reprocessing in the circular factory as a coordination of additive and subtractive machining technologies using multi-sensory process monitoring

3.2 KC2 Prediction for pairing and reprocess of the embodiment

The prediction of function fulfillment for pairing and reprocessing decisions within the circular factory uses the component recombination scenario. The scenario starts with an order to create a suitable product generation $G_{i=n}$ for which the factory control system queries the storage and product architecture for component instances from previous and current product generations to identify potential assembly configurations, e.g. spindle shafts and pinion gears. Based on data from diagnostics (product architecture, functional fulfillment, and reliability), the factory control system performs a decision based on to determine whether the candidate assembly should proceed for reassembly, be reprocessed, or be rejected, thereby supporting cross-generational pairing decisions. Knowledge from functional modelling is used to determine the suitability. E.g. the surface roughness shows no significant effect on functional behaviour in the represented range of spindle shafts in storage and degraded surfaces can be reused. However, a diameter change can be critical and also shows interaction with defects like scratches which need to be considered in reprocessing decisions. From reliability modelling, bearing-related faults and shaft misalignment are identified as dominant contributors to excessive vibration. Markov states distinguish healthy, degraded, and failed conditions, enabling time-dependent reliability assessment. Further, geometric and material reliability are distinguished, as they need different modelling and testing approaches (e.g. Palmgren-Miner damage accumulation or Paris-law crack-growth analysis for investigation)[10]. Based on this, the reprocessing capabilities of the circular factory are used [12] (see Fig.4).

Remaining and emerging challenges are the model-based integration of relevant uncertainty sources into test bench data, linking instance-specific degradation, manufacturing variation, and design changes into a predictive model of functional behavior. The immense modelling and testing effort for reliability investigations, which is already challenging in linear production, remains an issue in the circular factory as well as the limitations in reprocessing technologies.

3.3 KC3 Design for Circular Factory

Based on structural reliability modeling and reprocessing decisions, insights can be derived for Design for Circular Factory. For example, bearing-related faults and shaft misalignment should be considered when designing future product generations of the angle grinder. Moreover, criteria for suitable development and value-retention paths should be informed by functional thresholds, material limits, and predictive uncertainty.

The three elements scenario-based requirement derivation, cross-generational product analysis, and reference architecture modeling address future needs and benefits, reusable knowledge and their integration into a model-based reference architecture. The methodological elements shown in Fig.5 link user and customer scenarios and needs, product requirements, functions, and physical structures in an integrated ontology and system model, allowing for a reference product architecture that supports consistent and traceable cross-generational design decisions. [8]

Scenario-based requirement derivation clusters scenario elements into actor, device, location, and activity, allow usage and procurement contexts to be translated into requirements for the development of circular products and production systems. These scenarios are used to develop products that are both suitable for the Circular Factory and relevant for stakeholder needs and benefits. [13]

Cross-generational analysis of existing product generations using the model of SGE – System Generation Engineering compares successive product generations and identifies subsystems with high potential for cross-generational remanufacturing. For this, the core factors geometry, material, surface, interface, and solution principle are used. For example, the spindle shaft of the angle grinder shows recurring geometric features across investigated generations and even across different manufacturers. The fit of shaft and bearing influences vibrations, so a design change in the tolerance field towards a transition fit can increase its suitability for the Circular Factory. These design decisions directly influence Circular Factory planning, since they affect requirements for assembly, measurement technologies, and reprocessing capabilities. The characterizing core factors make development paths explicit and provide a basis for linking design decisions with value-retention paths, stakeholder needs, product profiles, and production-related objectives. Based on scenario-based requirements and cross-generational product analysis, the reference architecture model serves as the central integration model for Design for Circular Factory. It provides a system-specific, model-based description of the perpetual innovative product at the domain level. Through a model-based systems engineering approach, all relevant information is made accessible in a system model. Stakeholder-specific viewpoints allow product developers,

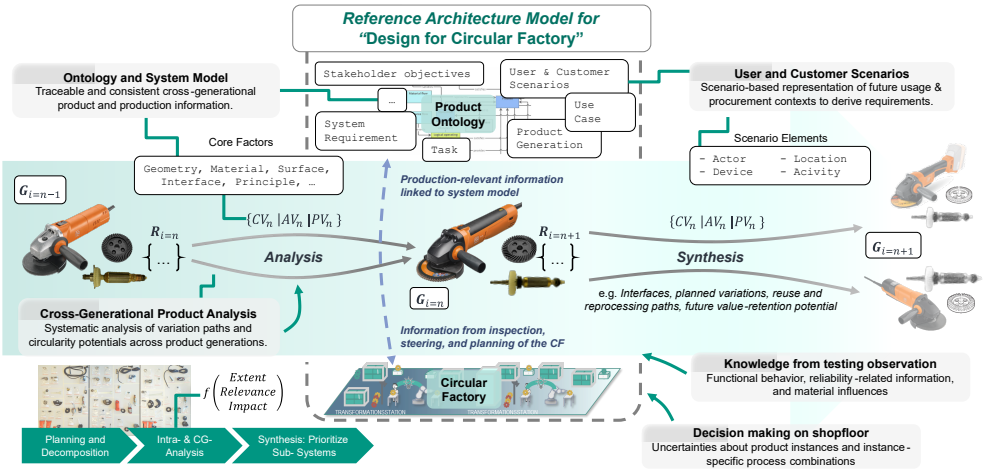


Fig. 5 Model-based support for Design for Circular Factory integrates ontology-based product information, product architecture views, variation paths, and insights from Circular Factory operation

production planners, and factory control to access the information required for their respective decisions. [14]

Remaining and emerging challenges arise from the continuous refinement of the integrated system model. Scenario-based requirements, cross-generational variation knowledge, instance-specific condition information, and production system capabilities have to be linked to support the prospective synthesis of circular product generations. In particular, design decisions have to balance stable interfaces and standardization with the need for technical novelty and changing stakeholder needs. The evaluation of reuse, reprocessing, and technological updating potentials requires suitable criteria that link product architecture decisions with functional fulfillment, reliability, and production system constraints.

4 Discussion and conclusion

The research question *Which challenges and opportunities emerge in product analysis, reprocessing, and design in a circular factory for perpetual innovative products?* can be answered as follows:
On one hand, very specific and highly sophisticated models and methods are needed to address challenges in the specific areas of analysis, reprocessing and design, while on the other hand, compatibility of the developed models and methods is needed to ensure their benefit for the circular factory. The main opportunity lies in the combined expertise present in the researchers developing models and methods from their field of expertise, which enables efficient solutions for upcoming challenges regarding compatibilities.

In the analysis, a strong interaction between the quality of measurement and the functional model emerged, e.g., when standard measurements were unable to detect

characteristics essential to the functional model, or when characteristics were measured that the functional model could not integrate at all. Here, joint research e.g. between production modelling methods and embodiment descriptions present in design supported in identification and depiction of individual characteristics.

In reprocessing, especially the process parameters of additive manufacturing strongly influenced the characteristics and reliability of the systems. This complicates reliability prediction further as there is higher uncertainty to be considered than in new components without additional rework. However, with the enhances functional and reliability modelling, characteristics of the reprocessed products can be defined precisely, giving an estimate of how suitable certain reprocessing decisions might be.

In design for circular factory, overarching strategies must be informed by specific results from investigating the characteristics of the design, creating a challenge for design engineers. The systems generation engineering allows the bridge between these strategies and the characteristics as its variations can directly be linked to them.

A general limitation remains, as this research is conducted on a conceptual level, as the real-world industrial factory has yet to be built, where the developed models and methods can be implemented. This will be a necessary step to evaluate the overall success factors of the circular factory approach.

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