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RESEARCH

Remanufacturing production planning and control: Conceptual framework for requirement definition

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Abstract

In the era of environmental degradation and resource scarcity, the concept of circular economy (CE) has emerged as a pivotal strategy to transform the contemporary industrial landscape. As an integral component of the 10R framework, remanufacturing is emerging as a production strategy that revitalizes end-of-life (EOL) products to a like-new condition, fostering a more sustainable production and consumption. Despite its immense environmental and economic benefits, the implementation of remanufacturing practices is confronted with a multitude of challenges, including sourcing of EOL products, managing component variability, and arbitrary failure rates that result in major process inefficiencies. This paper embarks on the definition of functional and non-functional requirements for remanufacturing production planning and control (RPPC) to establish a systematic approach to address the existing challenges and uncertainties that arise in remanufacturing systems. Based on the synthesis of a comprehensive literature study, eight functional requirements and a total of 48 associated key performance measures are derived and contextualized in a coherent conceptual framework. This establishes a consensus to mitigate the impacts caused by uncertainty in remanufacturing. The feasibility of the conceptual framework is validated in an industrial case study with an OEM remanufacturer of electric power steering products. The findings of this research paper advance the field of RPPC and offer guidance to industrial decision-makers to evaluate and optimize their remanufacturing production systems.

Keywords Remanufacturing production planning and control · Functional and non-functional requirements · System design and evaluation · Uncertainty mitigation

Introduction

In the wake of rapidly evolving trends, regulations, and globalized production networks, the domain of circular economy (CE) has emerged as a transformative paradigm within the contemporary industrial landscape [21]. The relentless pursuit of sustainability, coupled with a

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heightened awareness of environmental stewardship among customers, has set the stage for a profound shift in the way how mankind view and manage resources [9]. Besides the rise of customer awareness, governments intensify their commitment to sustainability by defining regulatory frameworks and incentives that proliferate and promote CE endeavors (e.g., see Ogunmakinde [33] that reviews the regulatory CE framework in China, Germany, and Japan). In this shift, the emergence of remanufacturing represents a modern and circularity-oriented production strategy. While recycling, re-usage, or other CE methodologies rather lead to a downcycling of the respective end-of-life (EOL) products [5], remanufacturing upcycles products to restore or surpass their original specifications which adds value from an economical and an environmental perspective [15, 48, 49].

Remanufacturing represents a systematic industrial process that involves visual or electrical inspections, disassembly, reconditioning, assembly, and final testing to verify that the remanufactured part meets or exceeds the original product quality [15, 34, 56]. While this practice is immensely promising for the sustainable transformation, it is not without complexities and hurdles regarding the sourcing of old parts (so-called cores), the involved value streams as well as the sale to the final customer [56]. Without sufficient production planning and control (PPC), these factors may compromise the viability of remanufacturing systems. In literature a variety of quantitative and qualitative approaches are outlined to tackle particular remanufacturing challenges. However, when it comes to the applicability and transferability of methods, Lage Junior & Godinho Filho [24, 10] state, that there is "little agreement between theory and practice", and remanufacturing PPC (RPPC) activities are either simplified or outsourced .

One reason for that may be the lack of requirements for RPPC. While there are singular solutions for particular problems, literature lacks a coherent framework to evaluate the feasibility of remanufacturing systems, or guidelines to design RPPC systems. Hence, the objectives of this conceptual research paper encompass:

1. Definition of functional requirements (FR) and non-functional requirements (NFR) for RPPC based on its identified challenges and complications.
2. Association of FR and NFR for RPPC with the main uncertainties within remanufacturing operations, with substantial measures to decrease the impacts caused by uncertainty.
3. Outline a coherent structure for requirement definition for RPPC to bridge the gap between theory and practice for sufficient remanufacturing system design, and mitigation of remanufacturing challenges for industrial decision-makers.

To meet the defined research objectives a multi-stage literature review is proposed. After a lack of requirements for RPPC is identified, a systematic process for their definition is proposed considering requirement definition literature. Here, the most prominent challenges are outlined and subsequently addressed. While FR are crucial for the functionality of RPPC systems, the NFR assess the system's performance. Thus, the most relevant key performance indicators (KPI) in RPPC literature need to be associated with the FR. Here, it is vital to consider the arising design constraints and uncertainties which are neglected in previous KPI-based studies. Finally, the different concepts are merged into a coherent structure; the conceptual framework for requirement definition for RPPC is outlined, considering the FR, NFR, constraints, and drawing a uni-direct relationship between the NFR and the impact caused by uncertainty. This depicts a novel approach that enables remanufacturing enterprises to identify RPPC challenges, and mitigate the impacts caused by uncertainty. The conceptual framework and its applicability is evaluated in an industrial case study of an original equipment manufacturer (OEM) remanufacturer. The systematic analysis of this case helps both industrial decision-makers and governmental regulators to formulate guidelines and directives to enhance the visibility remanufacturing production systems, and its associated complications

The remainder of this paper is structured as follows. Section "Literature review" comprehensively reviews the literature in the field of RPPC. In Section "Conceptual framework for requirement definition of RPPC", eight functional requirements for RPPC are defined, and the most prominent KPIs along the constraints and uncertainties are associated; furthermore, the conceptual framework for requirement definition is outlined. Section "Case study: OEM remanufacturer of EPS" evaluates the applicability of the developed framework in an industrial case study. Afterwards, the results are discussed in Section "Discussion". Finally, Section "Conclusions" draws concluding remarks and outlines recommendations for further research.

Literature review

To fulfill the objectives of this study, the literature review elaborates on functional and non-functional requirements for RPPC. We conducted a comprehensive review following the methodology outlined in [47]. The article assessment is based on the following criteria:

1. Articles should focus on remanufacturing and production planning or production control and requirements. As the literature regarding functional requirements is scarce in remanufacturing, we further incorporated performance measurements and indicators as a representation of non-functional requirements. Thus, we used iterative keywords such as "remanufacturing AND (production control OR production plann*) AND requirement*" OR "remanufacturing AND (production control OR production plann*) AND (performance measure* OR performance indicator* OR key performance* OR KPI*)".
2. To assess the most relevant literature in the field, the mentioned keywords were searched in the SCOPUS database and in Google Scholar. An additional search was conducted in major publishers such as Elsevier, Springer, and Taylor and Francis. To ensure high academic standards we only considered peer-reviewed journal articles and conference proceedings that are written in English. After the search was conducted we screened title, abstracts and relevant keywords to further filter the article collection. The shortlist was finished after full-text analysis of the literature.

The literature review is structured as follows. Firstly, a brief introduction about RPPC is given. Afterwards, major challenges and mitigation strategies of operational RPPC are highlighted, followed by a summary of requirement definitions and performance measures in that field. Lastly, the identified research gaps that we attempt to close are shortlisted, emphasizing the focus of this conceptual research paper.

Remanufacturing production planning and control

Unlike PPC in manufacturing systems, research on RPPC is relatively new but continuously evolving [11, 17]. In contrast to traditional manufacturing that operates based on virgin materials, remanufacturing relies on cores that return after their period of usage to the remanufacturing facility [15, 48]. Besides the positive sustainable impact from an environmental perspective, the rationale behind remanufacturing is, to upcycle EOL products to a technical sufficient and like-new condition and sell them for a discounted price to customers [15, 48, 49]. Similarly to the ordinary manufacturing operations, the customer and its satisfaction play a central role in remanufacturing operations, thus, it is crucial to ensure structured decision-making, adherence to quality standards, and resource optimization to satisfy customer demands [29, 53]. Upon arrival of cores, the remanufacturing process includes a visual, mechanical or electrical inspection, the disassembly, component cleaning, reconditioning and reprocessing of usable components, replacement of spare parts, reassembly, and testing to verify its original specification [15, 49, 56]. A typical remanufacturing production system is portrayed in Fig. 1.

According to Rizova et al. [38], the PPC of remanufacturing activities is subject to the planning horizon. The planning horizon refers to a time-dependent decision-making to execute strategies with multiple objectives over a long period of time; traditionally, the planning horizon considers a strategic, a tactical, and an operational planning dimension [53]. While the strategic dimension takes long-term decisions such as core collection strategies or product design into consideration, the operational dimension is concerned with process planning and scheduling; the tactical dimension represents an intermediate level for production planning and inventory management [38]. Considering the planning horizon of decisions, Junior & Filho [17] point out that the main purpose of RPPC is the optimization and control of inventory levels, mastering production schedules, and planning production capacities. While an integrated decision-making considers all three dimensions, this paper has a distinct focus on the operational and tactical level; however, implications and inter-dependencies to the strategic level are drawn.

Challenges and mitigation strategies for RPPC

Since remanufacturing parts are based on EOL products, the complexity of these processes increases significantly. Aside from the uncertainty regarding supply and demand, Tolio et al. [49] argue that the variability of input materials also effects the quality of the output materials. This complicates effective resource allocation and adherence to quality standards that generates pressure on the operational costs; thus, traditional decision-making models that are applied in general manufacturing systems are not, or only partly applicable in remanufacturing [38]. From an RPPC perspective, the main challenges that lead to major process inefficiencies and increased production costs include:

- uncertainties regarding the timing, quantity, and quality of supplied cores [4, 27, 28],
- imbalance of core recovery and customer demand [17, 31, 44],
- human-labor involvement [14, 49, 51],
- arbitrary failure rates of disassembled cores and procured components [28, 36],
- variable processing times [36, 49],
- technical incompatibilities [4, 13],
- component variability [18, 25, 56].

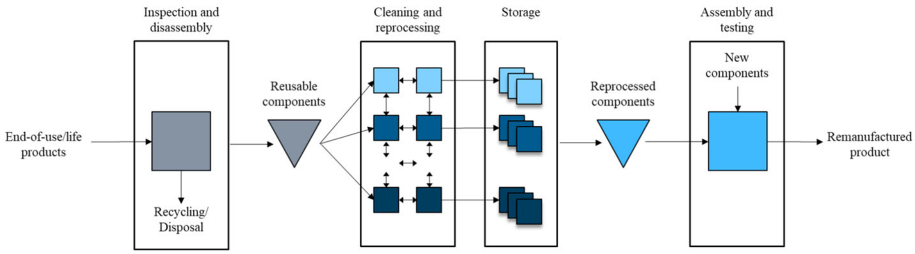

Fig. 1 Remanufacturing production system (adapted from [15, 56])

Despite relationships and contractual agreements between remanufacturing facilities and their reverse logistics suppliers, most information regarding the arriving cores is unknown. According to Bouzon et al. [4] this is caused by uncertainties that reverse logistics provider face themselves, operating in circular supply chains. Accompanied with the demand uncertainty of potential customers this imbalance of supply and demand is described as one of the biggest challenges for RPPC [17]. In literature, there are different approaches to mitigate them and enhance the planning and control of remanufacturing systems. Here, Minner & Kleber [32] propose a deterministic dynamic model to find optimal costs in seasonal product return and recovery time intervals under linear cost function assumption. Based on their findings, Kleber et al. [22] propose a dynamic model that considers core supply from a single source with a single quality, and multiple demand streams with variable product variants and qualities; helping practitioners to decide whether product recoveries should be sold immediately or put on stock for future demands with a higher profitability. For demand forecast, Matsumoto & Komatsu [31] developed a time series analysis under seasonality and OEM sales data consideration with an improved error rate over traditional methods for the remanufacturing of starters and alternators. Considering uncertain core supply and customer demand constraints, Gervasi et al. [3] propose a quantitative algorithmic approach to optimize lot sizes. In their study, Liu et al. [30] find that a safety stock of core components is required to fulfill customer demand in a dynamic environment with supplied core quality uncertainty.

For the execution of remanufacturing process steps, human-labor involvement is mentioned as a challenging factor. While Vogt Duberg et al. [51] highlight the importance of a highly skilled manual workforce, Tolio et al. [49] argue that this encourages remanufacturing facilities relocating to low-wage countries. However, this may cause higher logistics costs, loss of reputation and higher failure costs due to inadequate training opportunities. In their systematic review, Rizova et al. [38] show that literature lacks labor utilization models to optimize the deployment of workforce to optimize remanufacturing costs. In an attempt to close that gap Hoffmann & Knorn [14] develop a dynamic optimization model for resource allocation considering failure occurrence, versatility, and learning capabilities. To decrease the reliance on human labor, the implementation of collaborative robots [13] or vision-based technologies to automate visual sorting processes [18, 43, 54] depict viable solutions.

As remanufacturing operations take place at the end of a product's life, this may be multiple months or years after the product's series production. Throughout this time, the technical properties might have changed and their components may vary heavily [25, 56]. In addition, some cores might be non-destructively disassemble-able since remanufacturability is rarely considered in the ordinary research & development (R&D) processes [15, 23]. The non-durability of certain parts may additionally cause fatigue within the components (such as cracks or tears) that cannot be identified through a simple visual or electrical inspection [28, 57]. This causes a multitude of issues like arbitrary failures of components and leads to variable processing times, poor machine efficiency and higher production costs [13, 49]. For high product variability environments, Yu & Lee [56] propose a mixed integer programming algorithm to optimize the tardiness within the remanufacturing process organization with a focus on disassembly, reprocessing, and assembly job-shops. To improve overall process efficiency, Kurilova-Palisaitiene et al. [23] apply lean management methodologies to improve the remanufacturing lead time of four representative case companies. To further increase the continuity of the material flow, Paschko et al. [36] elaborate on a reinforcement learning algorithm that outperforms traditional lean management methodologies according to their simulation-based analysis. To increase the utilization of these worn-out parts, Li et al. [25] propose a systematic reverse engineering framework to enhance remanufacturing processes and tackle product variability.

Requirements for RPPC

Advancements in the field of RPPC are strongly underrepresented. Despite the vast challenges in this field, less than 1% of PPC requirement publications focus on remanufacturing in contrast to traditional manufacturing. Synthesizing the literature shows that publications either focus on product remanufacturability [15, 20, 34, 37], specific process requirements [18, 19], or requirements for smart remanufacturing systems [49]. Furthermore, the notion of requirement is not further distinguished into functional and non-functional aspects.

The field of product remanufacturability and its design concerns is constantly evolving due to the increase of governmental and customer attention [12]. Here, Ijomah et al. [15] developed design characteristic that either improve or impede remanufacturability of cores; these include the durability of materials, the joining techniques of the components, and features that prevent remanufacturing or jeopardize its profitability. In the study of Ramoni & Zhang [37], the authors evaluate product design stages by using an entropy function to assess the degree of disorder and its implications towards remanufacturability. Omwando et al. [34] evaluate product remanufacturability based on a bi-level fuzzy analytical decision-support tool that encompasses technical, economical, environmental and resource utilization aspects. For the further advancement of remanufacturing into the era of Industry 4.0, Kerin et al. [20] developed an asset model for product digital twins in remanufacturing; the authors define requirements for that digital twin derived from prevailing remanufacturing challenges. For an effective remanufacturing system, the planning and control of processes and process steps is crucial [38]. In Kamper et al. [19], the authors conducted a survey to derive the most prominent challenges for RPPC of electric vehicles. According to the authors, these challenges guide literature and decision-makers in defining requirements in this field. In their paper, Kaiser et al. [18] developed and applied a concept for autonomous quality control of returning cores for autonomous remanufacturing decision-making. In the era of Industry 4.0, Tolio et al. [49] define five requirements for smart remanufacturing systems; these include high adaptability to product and market condition, high level of automation, availability and traceability of information, high level of ergonomy and safety in human-centric environments, and application of advanced decision support tools based on data analytics within cyber-physical systems.

Performance measurements for RPPC

While functional requirements depict fundamental components that a system must encompass, non-functional requirements are concerned with performance and specific quality requirements. In the context of RPPC, they can be depicted by key performance indicators (KPI). KPIs are used in different industrial sectors and bridge the gap between the current and desired performance of a system [10]. In the most cases, KPIs are quantitative metrics that are measured or calculated. In dependence of the system, qualitative KPIs can be also useful. While Graham et al. [10] and Asif et al. [2] rather define and investigate quantitative KPIs for RPPC, Ansari et al. [1] focuses on a mix of qualitative and quantitative performance measures. In the development of their remanufacturability index, Omwando et al. [34] transforms qualitative measures into quantifiable metrics. In Graham et al. [10], the authors developed a qualitative Balanced Scorecard that distinguishes different quantitative KPIs in the context of RPPC into different categories; the applicability of the framework is tested in a high volume and low price as well as a low volume and high price remanufacturing scenario. For the developed remanufacturability fuzzy model in Omwando et al. [34], the foundational dimensions are based on qualitative and quantitative KPIs that favor RPPC. Ansari et al. [1] gather the 20 most important KPIs for remanufacturing supply chains among the SCOR framework (i.e. plan, source, make, deliver, and return); afterwards, the different KPIs are categorized either into cause or effect relations using grey DEMATEL methodology. In their publication, Asif et al. [2] develop a system dynamics model for closed-loop supply chains and analyze its behavior by KPIs.

In the context of RPPC, relevant KPIs include those specifically for remanufacturing and others that are used in traditional production systems. The most important KPIs based on the conducted literature review are summarized in Table 1. Here, the KPIs depict NFR associated with the defined FR; additionally, constraints and uncertainties are outlined. This paper has a particular focus on KPIs for RPPC from an economical perspective; for environmental-related KPIs, Sherif et al. [45] provide a comprehensive overview.

Research gaps based on literature review

Based on the synthesis of the previous subsections, the following shortlist summarizes the research gaps that we address in this paper:

1. For more than two decades, remanufacturing faces operational and tactical challenges that impede an efficient execution of production processes [11, 17, 38]. For a successful remanufacturing, RPPC is crucial [51]. Similar to the development of a product, production processes (i.e. remanufacturing processes) need requirements for their sufficient planning and control. In contrast to traditional manufacturing, the literature concerned with RPPC requirements is scarce. From an industrial perspective, Lage Junior & Godinho Filho [24] show that companies avoid RPPC activities by simplification or outsourcing. Thus, we identify the lack of requirements for RPPC as a pivotal research gap. This includes both functional and non-functional requirements for RPPC. In this context, FR provide guidelines to establish and enhance RPPC, NFR support and optimize decision-making to form effective RPPC systems.
2. For an effective planning and control from a NFR perspective, the evaluation of performance measure is fundamental [10]. This incorporates general KPIs for PPC and those, specifically applicable to remanufacturing [1]. While literature contains different frameworks that qualitatively organize KPIs among different categories (e.g., Graham et al. [10]), the interaction and interrelation among these categories is unclear. This depicts an important foundation to identify inefficiencies within a system to overcome the challenges for RPPC.
3. The prevailing uncertainty is acknowledged as one of the biggest impediments of successful RPPC. The different types of uncertainty are well studied but not transferred to performance measurement systems, or only qualitatively mentioned [1, 10]. Effective strategies to decrease the impact caused by uncertainties within RPPC systems are missing [40]. Hence, the identification of effective measures to mitigate impacts from uncertainty represent another research gap within RPPC systems and is closely aligned with the current lack of requirements. Their implications drawn within an integrated decision-making could help industrial decision-makers to mitigate risks and pave the way for more successful remanufacturing operations.

The above mentioned research gaps in the field of RPPC justify the rationale and objectives of this conceptual research article.

Table 1 Functional and non-functional requirements for RPPC

R_i	Functional requirements	Non-functional performance and quality requirements	Constraints	Uncertainty consideration	References
R_1	Design for remanufacturability	(1) Number of managed BOMs (2) Number of concessions (3) Design parameter entropy (4) Function entropy (5) Remanufacturability	EOL time constraint	Specific product limitations, material composition, BOM	[1, 10, 12, 15, 23, 34, 37, 49, 51]
R_2	Demand of remanufactured products	(1) Availability of sales data (2) Demand forecast accuracy (3) Demand backlog (4) Shipment of products (5) Product cannibalization (6) Demand delivery delay	Data quality and consistency, Market volatility, Competitor behavior, Forecast model limitations, Price constraints	Uncertain demand	[1–3, 17, 19, 22, 23, 31, 49]
R_3	Supply of cores	(1) Availability of (OEM) sales data (2) Supply forecast accuracy (3) Supply delivery delay	Data quality and consistency, Seasonality, Supply chain disruptions, Forecast model limitations	Uncertain supplied quantity and variant	[3, 4, 17, 19, 22, 23, 26, 32, 49]
R_4	Remanufacturability of cores	(1) Availability of quality data (2) Quality forecast accuracy (3) Delivery quality (4) Core / product ratio (5) CCD (6) Product salvage rate (7) Component salvage rate (8) Core disposal rate	Detection of remanufacturability, data quality and consistency, model limitations	Uncertain quality, material composition, BOM, random failures of cores and components	[17–19, 27, 28, 34, 49, 55]

Table 1 continued

R_i	Functional requirements	Non-functional performance and quality requirements	Constraints	Uncertainty consideration	References
R_5	Traceable value stream processes	(1) Number of managed BOMs (2) BOM compatibility (3) Availability of process data (4) Cycle / lead time (5) Failure rate per process (6) CCD / WIP / CCA (7) Costs per process (8) Product cost / margin (9) Process digitization	Data quality and consistency, delayed data reporting, random failure, process digitization, variability of process time, detected remanufacturability, scheduling model limitations	Uncertain supplied quantity and variant, uncertain demand, BOM, random failures of cores and components	[18, 20, 23, 28, 36, 49, 51, 56]
R_6	Human workforce	(1) Personnel saturation (2) Failure rate per resource (3) Hours per unit (4) Product / process versatility	Capacity limit, productivity constraints, learning capabilities, versatility constraints	Random failures of cores and components	[10, 13, 14, 18, 49, 51]
R_7	Production assets and tools	(1) Availability of asset data (2) OEE (3) Failure rate per resource (4) Cycle / lead time (5) Product / process versatility	Capacity limit, Productivity constraints, human control instance, handling constraints, versatility constraints	Random failures of cores and components	[2, 10, 28, 49, 51]
R_8	Safety stock of components	(1) Availability of inventory data (2) Number of managed BOMs (3) Core / product ratio (4) Component availability (5) CCD / WIP / CCA (6) Cycle / lead time (7) New component cost (8) Product cost / margin (9) Demand backlog	Physical maximum inventory level, cost limit, data quality and consistency, seasonality, demand and supply forecast limitations, core variability and detected remanufacturability, inventory model limitations	Uncertain supplied quantity and variant, uncertain demand, BOM, random failures of cores and components	[10, 18, 20, 23, 28, 42, 44, 50, 56]

BOM: Bill of material; OEM: Original equipment manufacturer; CCD: Core class distribution

Conceptual framework for requirement definition of RPPC

Design of the conceptual framework

For the design of the conceptual framework, it is mandatory to introduce the concepts of system design and requirement definition. According to Ross and Schomann [41], the definition of requirements is essential for the successful design of a system and, its anticipation results in the duplication of work, cost increases and missed schedules. In applied research and in an industrial context, the notion of requirements is closely linked to their fulfillment as a quality assessment (e.g., fulfillment of quality requirements in the context of ISO 9001:2015). In both cases, the foundation of the respective (quality) requirements is defined by an external stakeholder (e.g., customers, governments, suppliers, etc.) in an early stage of the system's development process [35, 39]. To shed light on these complexities out of a generic perspective, Ross & Schoman [41] designed a process to subsequently define requirements on a system level; the steps include:

- Context analysis ("why are we doing it?"),
- Functional specifications ("what are we doing?"),
- Design constraints ("how do we proceed from here?").

From a system perspective, the subsequent steps firstly elaborate "why" the system should be created and which technical, operational, and economical boundary conditions are surrounding the endeavor. While the functional specifications describe the functions that the anticipated system must fulfill, the design constraints describe boundary conditions. Here, the notion of functional specification is closely associated with the terminology of functional requirements. Additional to these functional requirements, Robertson & Robertson [39] and Glinz [6, 7] emphasize the incorporation of non-functional requirements as a sub-class within the requirement definition framework. These non-functional requirements describe qualities of a system to increase its performance, usability or accuracy; that are also subject to its design constraints [39].

Software architecture is designed based on customer requirements to provide the right solution for the right problem. Transferring this goal-oriented approach for requirement definition to the context of manufacturing systems (i.e., remanufacturing systems) [46], requirements can be defined as the foundation to establish an effective planning, execution, and control of production processes to achieve reliable and cost-efficient products that adhere to the defined quality standards. Thus, the requirement definition of RPPC systems comprehensively addresses its prevailing challenges to fulfill the outlined definition considering the boundary conditions of remanufacturing. Therefore, this paper develops a conceptual framework for requirement definition.

In academia, the conceptual framework is a widely applied tool and terminology that is used to contextualize different concepts into a coherent system that conceptually addresses the identified research gaps. To find a common understanding of this term, Jabareen [16, 51] defines the conceptual framework as "a network or "a plane," of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena". In Fig. 2, the process to establish the conceptual framework is outlined. According to Kamper et al. [19], the defined FRs are thorough, when the system's challenges are considered. For performance measurement within the defined system, NFR and associated design constraints are outlined. In the context of RPPC, design constraints encompass system constraints such as boundary conditions for particular FR and prevailing uncertainty considerations that are

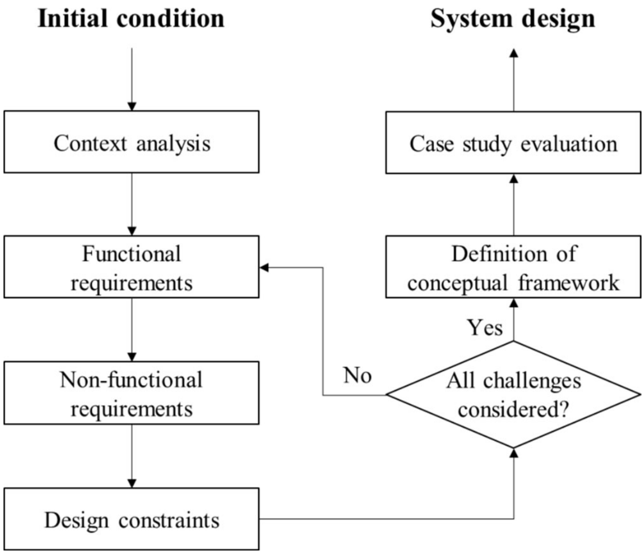

Fig. 2 Process for requirement definition (adapted from [7, 41])

inherent in remanufacturing systems. As depicted, the applicability of the framework for system design is evaluated using an industrial case study.

Requirement definition for RPPC

Following the outlined process in Fig. 2, we defined eight functional requirements for RPPC. These requirements include: Design for remanufacturability, demand of remanufactured products, supply of cores, remanufacturability of cores, traceable value stream processes, human workforce, production assets and tools, and safety stock of components.

While the different FR enable a functional RPPC, the NFR enhance the system's performance in creating remanufactured products for the final customer and thus, increase its viability. In Table 1 we associated the most relevant NFR (i.e. KPIs), constraints and uncertainties for RPPC with the eight FR. An explanation and formulas to calculate the NFR are provided in the Appendix.

Design for remanufacturability

As outlined by a variety of authors such as [12, 15, 37, 49, 51], we propose *design for remanufacturability* as the first functional requirement for RPPC. The design for remanufacturability anticipates the material and component composition, durability, and ensures the non-destructive disassembly. While the durability and the non-destructiveness are crucial for the remanufacturability of cores, other aspects such as the material and component composition, technological complexity, modularity, and compatibility of BOMs enhance the effectiveness and resilience of the remanufacturing system. However, since remanufacturability is rarely considered in ordinary R&D processes [15, 23], effective feedback loops from the control system to the R&D processes must be ensured to tackle this design constraint. This is particularly relevant for contract and OEM remanufacturer, since independent remanufacturing firms are not associated with their upstream R&D processes.

Demand of remanufactured products

The customer-oriented demand was outlined in the context of traditional manufacturing and remanufacturing products in [3, 17, 19, 22, 49], thus we define *demand of remanufactured products* as our second functional requirement for RPPC systems. The demand of remanufactured products is concerned with the fulfillment of customer orders at the right time, quantity, and quality to enable the viability of remanufacturing systems. As this FR is concerned with an inherent uncertainty [17, 31, 44], demand forecasts based on previous and estimated sales data is crucial for an effective RPPC. When predicting the market demand for remanufacturing products, enterprises face data quality issues coupled with limitations towards the forecast model assumptions such as seasonality or competitor behavior. To enhance forecast accuracy and reliability, kurilova-palisaitiene et al. [23] propose the establishment of an extensive customer relationship management as a qualitative NFR.

Supply of cores

The prevailing challenges associated with the supply of EOL products and their impact on PPC is discussed in [3, 17, 19, 22, 32, 49]; therefore, we define the *supply of cores* as a FR for RPPC. From a control-oriented perspective, the supply of cores considers the time and quantity of arriving core variants at the remanufacturing facility. Similarly to the demand of remanufactured products, this FR is somewhat dependent on the external reverse logistics supplier and their mutual relationship [23] and thus, can only be forecasted with a certain accuracy. The reliability of the model is limited to the assumptions made and the competitor's behavior. However, the main uncertainty considerations are passed on subsequently by the reverse logistics provider (e.g., Bouzon et al. [4]). Therefore, performance tracking of the supplier performance coupled with an extensive supplier relationship management is crucial.

Remanufacturability of cores

The quality and condition of the arriving cores has been highlighted as one of the most significant challenge of remanufacturing operations [1, 17–19, 27, 28, 34, 49, 55]. Hence, we define *remanufacturability of cores* as a FR for RPPC that is concerned with the individual core condition at its state of arrival, considering the decision-making upon subsequent processes such as the core's disassembly or scrapping and the required processes to remanufacture the usable EOL components [1]. To limit the impact of the prevailing uncertainty [18, 27], a core quality assessment including a forecast towards the visual detection of failures, the reconditioning efforts, and core and product salvation is vital. These information also help to predict and mitigate random failures of cores and components in subsequent processes. The forecast model is subject to model limitations, available information and the remanufacturability detection. While OEM remanufacturer have access to the design information, independent

[1] In the current literature, the core quantity and quality are mostly mentioned as one particular uncertainty and thus, challenge. As the decision-making upon the reaction towards R_2 and R_3 differs heavily, we specifically distinguished them in two FR. While the quantity of supplied cores can only be forecasted or improved by customer relationship management, the remanufacturability is highly dependent on the deployed resource to assess remanufacturability and the processes that executes the remanufacturability.

remanufacturer additionally face uncertainty regarding the core composition and architecture. For that reason, reverse engineering efforts are vital, as this can significantly increase the core / product ratio and thus, keep more products in circularity.

Traceable value stream processes

The importance of evidence-based information in process planning and execution is mentioned by different authors such as [8, 28, 49–52, 56]; thus, we define *traceable value stream processes* as functional requirement for RPPC. This FR is concerned with the possible routes and value streams for each individual core based on its state of remanufacturability as well as its associated product and process related information. This also encompasses the reverse engineering efforts to enhance the reuse of remanufacturing parts based on adjusted value streams. To minimize the uncertainty that arises from the variability of core components [18, 51, 56], arbitrary failure rates and the associated variable processing times [23, 28, 36, 49]; the traceable value stream processes require a continuity of information, data-driven adaptability, standardization, modularity and flexibility. Furthermore, frequent feedback streams to the control instance are vital to quickly react to process-related issues. Furthermore, according to Wang et al. [52] and Goodall et al. [8], the availability and analysis of process-related information positively impact the performance of the system, and decreases the impact caused by the inherent uncertainty.

Human workforce

For the fulfillment of customer orders with variable core and component quality, we define *human workforce* as functional requirement for RPPC. The human workforce represents a number of manual workers that operate within the traceable value stream processes to remanufacture supplied cores to satisfy customer demand. The human involvement is particularly relevant for remanufacturability decision-making. The variability of cores and their components represents a prevailing challenge towards visual inspection, disassembly, handling, and cleaning operations [13, 14, 18, 49, 51]. From a non-functional perspective, it is vital to measure the performance of each operator towards its productivity and failure rate under shift and learning capability considerations. As human operators possess more versatility than production machines, cross-sectional training and job-rotations are pivotal to increase their utilization for different processes and product variants. For the advancement of remanufacturing systems, human-robot collaborations to further increase ergonomic aspects and reduce errors could be considered.

Production assets and tools

In dependence of the respective remanufacturing process and product, the human involvement is dependent on the number of accompanied machines, thus we define *production assets and tools* as functional requirement for RPPC systems. The production assets and tools are necessary to inspect, recondition, or assemble certain remanufacturing products (e.g., Tolio et al. [49] or Liu et al. [28]), alongside the human workforce. The machine performance is measured by the overall equipment efficiency, the cycle and lead time, failure rate, and the versatility. These KPIs are subject to capacity constraints regarding the product, process, variant, and resource. Also, in some machines, a human control instance for final decision-making is required.

Safety stock of components

The quality and quantity imbalance of arriving cores and demand predictions have been mentioned as a major challenge in [18, 23, 28, 42, 44, 50, 56]. Thus, we define *safety stock of components* as a functional requirement for RPPC. While many scholars only consider the safety stock of core components, this FR additionally considers a buffer of spare parts to balance uncertainties regarding supplied cores, remanufacturability of cores, and customer demands. From a NFR, this includes the accessibility of relevant information regarding the existing BOMs, core / product salvation rate, cycle and lead time, component availability and related costs regarding products and processes. The prediction of the optimal inventory strategy is subject to physical spacing limitations, cost considerations, and data quality. Furthermore, the predictability is influenced by the forecast accuracy of the core supply and remanufacturability as well as the demand of remanufactured products.

RPPC system

As shown in Table 1, the KPIs of the FR depict specific goals where each NFR aims to maximize or minimize its value based on its particular goal. However, the specific goal might not contribute optimally to the overall aim of the system. For example, one specific goal of R_8 might be the minimization of the safety stock, and thus, minimize working capital. When based on the forecast of supplied cores, the demand of the following period can only be fulfilled with a higher WIP, this leads to a multi-objective conflict. For that reason, it is vital to consider a RPPC system that harmonizes the KPIs and their respective specified objectives to fulfill one global goal.

In the scope of this paper, the global objective refers to an operational or tactical goal that is aligned with the overall strategy of the remanufacturing enterprise. According to Rizova et al. [38] (as exemplified in the brief example), remanufacturing systems operate on multiple objectives such as the maximization of market share, salvation rate or the produced quality, or the minimization of total costs, lead time or disposed waste. However, the most important aim of the RPPC system is the optimization of its created profit, considering its constraints regarding the products, processes and resources, and the inherent uncertainty.

For profitability optimization a variety of factors must be considered in these quantitative models. Approaches to mitigate specific remanufacturing challenges are outlined in Subsection "Challenges and mitigation strategies for RPPC". However, mathematical models that integrate different KPI dimensions for global RPPC optimization are missing, especially considering the different kinds of uncertainty. Here, the definition of the FR and their associated NFR represents a significant foundation for a quantitative optimization of RPPC from a holistic perspective. This depicts an interesting gap for further investigation based on the findings of this conceptual research paper.

Conceptual framework for requirement definition

Following the process for requirement definition in Fig. 2, this section contextualizes the functional requirements, the non-functional requirements, the constraints and their uncertainty association in a coherent structure. The conceptual framework for requirement definition of RPPC is displayed in Fig. 3. We categorized the FR into three dimensions that include product-related, system-related, and process-related FR:

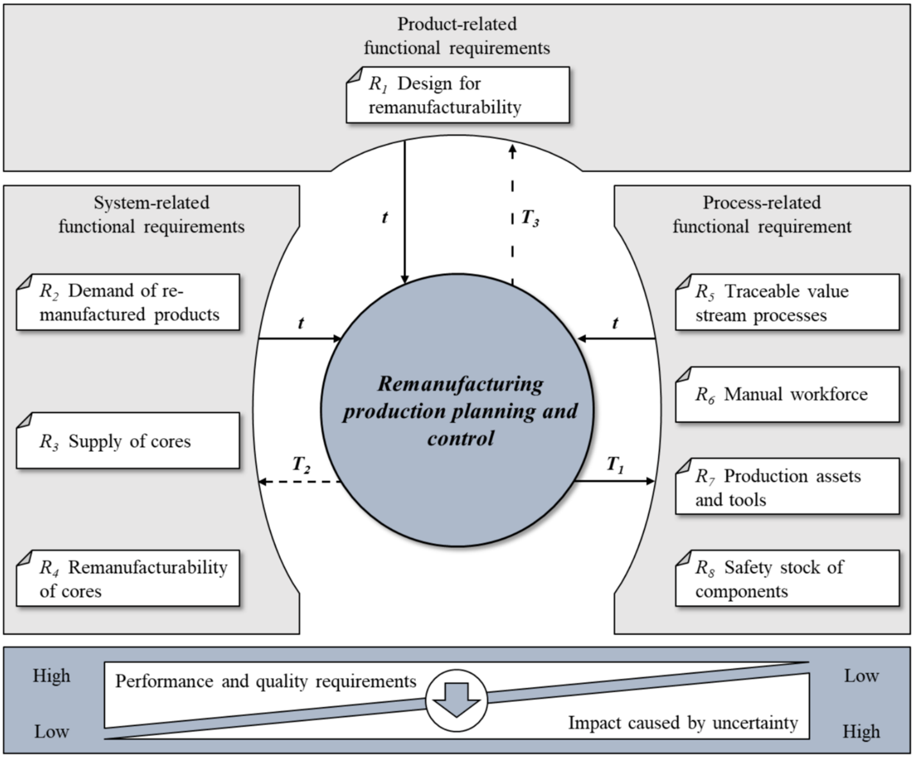

Fig. 3 Conceptual framework for requirement definition of RPPC

1. Product-related FR: The first dimension is concerned with the product requirements that are defined in the beginning of its life cycle. This means that when the product is either not designed for remanufacturing or subject to specific requirements that impede its operations, the RPPC is set to fail. In the case of contract or OEM remanufacturing, the feedback loop from the RPPC system to its product designers takes a long time. For independent remanufacturing firms, there is no communication channel available. However, the findings of the RPPC operations and this feedback are essential for the creation of future product types. As remanufacturability is mostly not considered in design stages (neither for OEM nor for independent remanufacturing), the product-related FR is subject to uncertainty.
2. System-related FR: The system-related FR are concerned with external factors that impact the RPPC system, considering the demand, supply, and remanufacturability. These external instances cannot be directly influenced by the RPPC system; however, we consider an indirect feedback loop as an efficient RPPC could decrease costs that have a direct impact on pricing adjustments that may lead indirectly to a higher market demand for remanufactured products. This feedback loop is shorter than the one of the product-related FR. Since the RPPC can only forecast R_2 to R_4, these FR are subject to uncertainty considerations that may impede the overall system.
3. Process-related FR: This dimension encompasses the process-related FR for RPPC. These are concerned with the capabilities that enable effective execution of the production operations. In contrast to the other two dimensions, the process-related FR have a direct

feedback from and to the RPPC system, and thus, can be directly adjusted. Each of the FR R_5 to R_8 is subject to capacity constraints such as limited workforce or machining capacity for specific product and process variants. However, considering the product-related and system-related FR, the resources within this dimension can be allocated and scheduled accordingly. Aside from the uncertainties towards the RPPC and its process-related capabilities posed by the product-related and system-related FR, uncertainties regarding R_5 to R_8 are subject to a dysfunctional RPPC. Thus, the process-related remanufacturing uncertainties can be dissolved to a minimal level by establishing an effective planning and control.

As outlined, the three dimensions and the direct or indirect consideration of decisions from the RPPC are subject to different time constraints and feedback frequencies. We assume that the system takes decisions at time t that are continuously provided by the NFR. Thus, the earliest time that a decision can be incorporated is $t + dt$. Here, we define the time-dependent relationship among the three dimensions as:

$$t + dt \leq T_1 \leq T_2 \leq T_3. \tag{1}$$

For an effective RPPC, it is crucial to minimize T_i with $i \in \{1, 2, 3\}$. The decisions taken at time t are subject to information availability regarding the FR that are expressed by the NFR and the objectives of the overall system (e.g., maximization of profit or minimization of costs). These NFR are allocated as performance and quality requirements within the conceptual framework. We derive here a uni-direct relationship between the performance of the system (measured by the NFR) on the impact caused by uncertainty. This means that a RPPC system with a high performance and quality level mitigate the impact caused by uncertainty. On the other hand, a RPPC system with a low performance and quality level from a NF perspective is highly impacted by the inherent uncertainties posed by the product- and system-related FR. In this context it is vital to take decisions regarding disturbances within a short period of time. Thus, it is imperative that the time interval t is minimized with a short feedback of T_i, particularly T_1. This is essential for real-time decision-making, and to increase the system's resilience. This feedback loop based on the measurement of KPIs depicts an effective strategy to address and mitigate the effects caused by uncertainty, and thus addresses the research gap highlighted by Ropi et al. [40]. This uni-direct relationship represents a novel approach within the advancement of RPPC.

As outlined within the three dimensions, the product-related and system-related uncertainties are caused by external factors such as supply of cores. The uncertainty of the internal processes is caused by a lack of information. To exemplify the uni-direct relationship an example is proposed.

The allocation of human labor in remanufacturing is outlined as a major impediments. One particular challenge regarding labor involvement is the subjective decision-making at the different remanufacturing process steps. Considering the decision of core remanufacturability, a wrong decision would either cause higher production costs or higher scrap rates that ultimately could result in less serviceable products to fulfill customer demand. When an increase of one of those KPIs (e.g., core disposal rate) is identified, the system or the different process-related FR and their associated NFR can be adjusted. This may either include a value stream process adaptation or the investment in training opportunities for human operators to decrease the identified weakness. As the uncertainty regarding the product-related and system-related FR is externally caused, it cannot be decreased as easily. Nevertheless, an effective RPPC that masters the process-related FR is more adaptable to changes and thus, more resilient towards the impacts caused by uncertainty. For example, the imbalance of core supply and demand of remanufactured products is highlighted as a major complication. Despite favorable forecasts, the supply and demand in remanufacturing are subject to uncertainty. This uncertainty may not be fully mitigated but its impact can be lowered by flexible safety stock or adjustable production capabilities.

As the previous examples showcase, the conceptual framework fills a vital gap in the field of RPPC to mitigate risks, tackle challenges and react to uncertainties in a systematic way to increase remanufacturing performance. While the framework focuses on the operational and tactical level, its implications are also relevant for strategic decision-making. This could consider to widen capability constraints by investing in more flexible or efficient machinery, the engagement in a customer or supplier relationship management to access more information about the upcoming demand or supply, or adaptions in strategic product design to enable a more effective remanufacturability. Furthermore, the concise structure of the framework helps to reveal operational challenges to establish regulations in this field.

Case study: OEM remanufacturer of EPS

To evaluate the feasibility of the developed conceptual framework for RPPC, an industrial case study with an OEM remanufacturer of electric power steering (EPS) is conducted.

Initial situation

The observed case company is an OEM remanufacturer. Hence, the company operates in a closed-loop supply chain that consists of the ordinary supply chain that produces EPS for new cars, and a reverse supply chain where EPS after their EOL are remanufactured for the automotive aftermarket. Despite the profitability of the remanufacturing business, the main objective of the OEM remanufacturer is the fulfillment of the delivery obligation period (i.e., a time period where the manufacturer is obligated to produce components for the automotive customer after the end of its series production). The requested demand until the end of this period is forecasted by the OEM remanufacturer. The OEM remanufacturer operates in a triadic relationship with the reverse logistics supplier and the automotive customer as both, supplier and customer are part of a collaborative partnership. This causes potential distress as the remanufacturing customer is aware of supplied core quantities and visually detectable core remanufacturability. The closed-loop supply chain of the OEM remanufacturer is outlined in Fig. 4.

The remanufacturing process corresponds to the one outlined in literature. Upon core arrival, the EPS are visually inspected and the good parts undergo a mechanical and electrical diagnosis. Each core that meets the specific product requirements is subsequently disassembled into its valuable components; spare parts like bearings and sealing elements are scrapped. Afterwards, the components are cleaned and mechanically reconditioned. All good parts are stored in an intermediate stock that separates the supply of cores and the assembly of remanufactured components. When a customer order arises the reconditioned components are assembled and finally tested under OEM series specifications to verify its functionality and performance. The remanufacturing is done upon customer demand on a contractual basis. When steering systems fall-out after final testing, another disassembly and diagnosis is executed to locate the root cause; when a subsequent final testing fails again, the respective remanufactured EPS variant is scrapped.

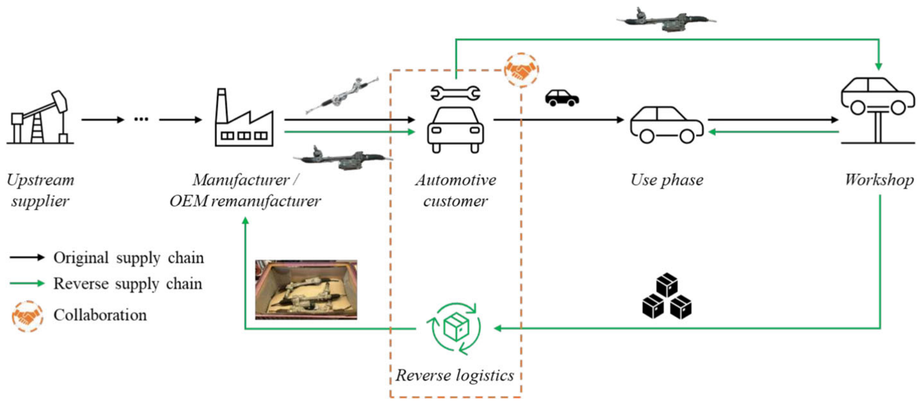

Fig. 4 Closed-loop supply chain of OEM remanufacturer

The remanufacturing of EPS is particularly interesting, as the product is a safety critical part with specific product requirements that is widely used in the passenger car segment. Furthermore, The EPS is characterized by an interplay of mechanical and electrical components. Figure 5 illustrates three axis parallel (apa) steering gear cores that are supplied by the reverse logistics provider. As shown, the outside of the steering gears are worn off but do not show any severe damage. However, the remanufacturability of the cores and its components are outlined in the design for remanufacturability requirements below. Each EPSapa consists of six main components that are considered for remanufacturing. These six components can be reused due to their longevity and durability; these include (order based on the component value, from highest to lowest):

1. Steering control unit (SCU),
2. ball nut assembly (BNA),
3. sensor unit (SU),
4. housing,
5. gearbox cover,
6. sensor cover.

Despite the information availability towards BOMs and R&D documentation, the RPPC faces similar challenges to those outlined in literature, particularly the ones caused by uncertainties arising from the system-level and process-level. Therefore, the conceptual framework for requirement definition is applied to analyze the initial situation and derive qualitative guidelines to optimize the current situation of the OEM remanufacturer.

Fig. 5 EPSapa cores and core components

Application of conceptual framework

For the application of the conceptual framework, the FR and NFR are assessed. As outlined in the previous Subsection, the OEM remanufacturer possesses each of the eight FR. In the case of the EPSapa remanufacturing, these are examined below:

- R_1 Design for remanufacturability: Generally, the electric power steering gears have an incorporated eco design that is suitable for remanufacturing. The main components of the core are connected via screws that enable a non-destructive disassembly. Furthermore, as the main body of the EPS is made from aluminum and steel, it is durable for at least one life. Currently, there are three different EPSapa product types in remanufacturing consideration; these are not compatible among each other. Each of those product types have different BOMs that are partly compatible. Especially the electrical components must be on the same technological standard with the same protocol to be reused for functional assembly. As EPS products are safety-critical parts within passenger vehicles, they are subject to specific requirements on core and component level. Firstly, it is mutually defined with the customer that EPSapa are only capable of remanufacturing when they have a maximum number of used kilometers tracked within the load counter. Therefore, each EPS that surpasses that level (even though it may look sufficient) is excluded for remanufacturing. Also, cores that display critical failures and thus, do not allow reading out the driven kilometers are additionally excluded. This is mainly due to a damaged electric control unit (ECU) that forms the SCU together with the motor. Even though, a disassembly of the SCU into motor and ECU could salvage the motor, this could cause particle infusion that damages the security system; therefore, despite a sufficient motor and a defective ECU, the whole SCU needs to be scrapped. Also, the SU cannot be non-destructively disassembled in its sub-components. Additionally, some of the SCUs contain tin contacts that should not be introduced into the market again, thus, SCUs with tin contact need to be scrapped as well.
- R_2 Demand of remanufactured products: The OEM remanufacturer is directly associated with the original parts producer of new EPS products. Hence, remanufacturing depicts an automotive aftermarket strategy to fulfill the delivery obligation after series production. The requested customer demand is defined in a contractual agreement. When the number of requested parts is not fulfilled, contractual penalties can be raised. However, as the automotive customer is involved in a collaborative partnership with the core supplier, the fulfillment of the demand requirements are highly dependent on the supplied cores and the communicated salvation rate. Independent of the contractual agreements and the demand requests, the communicated quantity may vary.
- R_3 Supply of cores: The remanufacturing system is supplied with cores by a reverse logistics provider that is associated with the automotive customer. The contractual agreement stipulates that a deposit for each core is paid; this deposit is repaid when severe damage is visually detected. This repayment option is only available for a limited number of weeks after core arrival and does not include fall-outs during electrical and mechanical testing. Similarly to the demand consideration, the supply of cores and core variant may differ from the ones communicated with the reverse logistics provider.
- R_4 Remanufacturability of cores: The remanufacturability of cores is subject to the design for remanufacturability R_1, its associated specific product requirements, and the supplied product variant R_3. To assess the remanufacturability, the mechanical and electrical capabilities of each EPSapa are inspected. This includes the functional testing of the steering gear and the verification of test criteria such as lock-to-lock test, yoke play between rack

and SU, and the tilt play of the BNA. For electrical testing the SCU is read-out and flashed for reuse in the remanufacturing process. When all of the testing factors are in a feasible range, the EPSapa is disassembled into its main components; after this process, the components are visually inspected individually. Based on the degree of worn-ness, the cleaning processes and reconditioning steps are defined. Reverse engineering is not considered in the scope of EPSapa remanufacturing.

- R_5 Traceable value stream processes: After the assessment of core remanufacturability, the different product variants undergo the required processes to fulfill the customer demand, that include cleaning, recondition, storing, (pre-)assembly and final testing. Since the variants of the EPSapa consist virtually of the same components, the cleaning and reconditioning processes differ among the different components but remain the same for all variants. Only one variant differs regarding pre-assembly that includes a dispense process on the inside of the housing and the gearbox cover. As the machine was industrialized to produce new steering gears, the color shades of the reused housing parts lead to production stops that may result in scrapping the components. After successful assembly of the main components and the spare parts, the remanufactured EPSapa variants undergo final testing to verify their like-new quality. Similar to the dispense process, the machine was designed for new steering gears, hence, it also leads to a variety of failure occurrences. After a remanufactured EPSapa has been verified as not sufficient, the variant is disassembled and analyzed. After re-assembly and an additional fall-out, the remanufactured EPS is scrapped. The information availability regarding the processes differ vastly; while the assembly and testing machine have an interface that is coupled with the enterprise resource planning (ERP) system, the information regarding visual inspection, disassembly, and cleaning are manually transferred into the system. This manual process is highly dependent on the operator and shift and can take up to one or two weeks to be integrated as bulked data.
- R_6 Manual workforce: Manual operators are crucial for the remanufacturing process of EPS. This is mainly due to the complicated handling of the cores as well as their value. In the case of the observed remanufacturer, human labor conducts the visual inspection, diagnoses the EPSapa mechanically and electrically, and executes the disassembly, reconditioning and storing. Only (pre-)assembly and testing are partly automated but require human feedback to proceed with the work flow. In addition, when a process stops due to a failure occurrence, the worker has to take the decision whether the part is scrapped or used for remanufacturing. The remanufacturing facility is on-shore located in a low to medium wage country. This causes a low level of identification with the job, and thus, a high fluctuation rate. This leads to some operators causing high scrap rates due to lack of experience, particularly in the disassembly, reconditioning, (pre-)assembly, and final testing.
- R_7 Production assets and tools: For EPS remanufacturing, the application of production assets and tools is vital. This particularly includes tools to read-out and flash the SCU to assess remanufacturability, tools to regrind screw threads as well as machinery to clean, assemble and test remanufactured gears. In the case of the OEM remanufacturer, the pre-assembly machines are only applicable to the respective EPSapa variant. The assembly and testing machine are universally applicable to all variants. However, the remanufacturing facility only encompasses one machine of each type. Aside from the remanufactured EPS gears, the pre-assembly and final testing machines also produce new small scale series that have priority. This creates bottlenecks, particularly regarding the identified failure rate occurrences.

- R_8 Safety stock of components: The remanufacturing facility possesses an inventory of safety stock of the main components that are considered for remanufacturing. An inventory of spare parts is uncoupled with the market as the parts are still available for purchase. The level of the safety stock is associated with the scrap-rates of the mechanical/electrical inspection and the disassembly of cores. An association with the fall-outs on the assembly and final testing is not drawn. Furthermore, the safety levels are not coupled with the varying supply and demand; the determination of the critical levels are calculated by assumption, without considering forecasts regarding R_2 to R_4.

Based on the FR, the NFR that measure the performance and quality of the RPPC of the OEM remanufacturer are assessed. For performance tracking a monthly report is established that depicts the key measures of the remanufacturing business. This report is evaluated in the engineering department and on management level to enhance decision-making. The main KPIs that the report encompasses are the supply of cores, the customer demand and the backlog, resulting from lower serviceable quantity of remanufactured products than the demanded quantity by the customer. Another key figure of the monthly report is the salvation rate of cores (input core ratio to output remanufacturing product ratio). This ratio is distinguished into the cores and components that are salvaged after visual inspection, disassembly (including mechanical and electrical diagnosis), cleaning, and remanufacturing production (including (pre-)assembly and final testing). Additionally, the efficiency of the assembly and test machinery is measured with the OEE. The effectiveness of manual operators is not tracked. As the final test bench has lead to regular fall-outs, the top three failures are under investigation and are tracked within a monthly period. The effectiveness of these failure mitigation strategy differs heavily.

In addition to the monthly report that evaluates the operational performance regarding the fulfillment of customer demand, the salvage rate of cores for remanufacturing products and the failure rates on the machinery, a business case calculation is executed at the end of every year. This calculation draws concluding remarks on the remanufacturing facility from a business perspective, evaluating the planned and the effective costs and profit on a component and product level as well as in sum. Based on these calculations, the average performance of the machines and operators can be drawn. The KPIs of the OEM remanufacturer with their tracked period are summarized in Table 2.

Analyzing the situation from an RPPC perspective shows that the information availability at time t is limited, which is mainly caused by information that are integrated manually into the system with a large time discrepancy. Therefore, the RPPC decisions at time t can only take limited parameters in consideration and the operational impediments are addressed with a time delay to the real events. This lack of information leads to a high level of uncertainty regarding the operations of the FR and NFR, especially on the process-level regarding R_6 to R_8. With a high uncertainty in the process-related FR, it is very difficult for the system to perform in an efficient way to fulfill customer demands. Another difficulty caused by information availability is the tracking of KPIs only on a monthly basis. High salvation rates in specific areas such as the diagnosis or disassembly might peak during certain shifts which could indicate training measurements of specific operators. Smoothing these effects on a monthly basis decrease the range of adjustment decisions. Thus, with the KPIs as the main decision-making tools the feedback loop, or T_1, of the RPPC system to the process-related FR is at least one month.

This planning horizon is far too large to execute effective operational measurements to optimize the system. The feedback loop that indirectly influence R_2 to R_4 has a similar cycle time as T_1. With a decrease of salvation rate after visual inspection, the FR R_4 might increase

Table 2 KPIs of OEM remanufacturer

Current KPIs	Unit	Tracking period	Associated FR
Failure rate - (Pre-)assembly - Final testing	%	Weekly	R_5, R_7, R_8
Customer demand	#	Monthly	R_2
Backlog	#	Monthly	R_2
Supply of cores	#	Monthly	R_3
Salvation rate of cores - Visual inspection - Diagnosis and disassembly - Cleaning and rework - (Pre-)assembly and final testing	%	Monthly	$R_4 - R_8$
Process costs	€/unit	Yearly	R_5, R_6, R_7
Product costs	€/unit	Yearly	$R_2 - R_8$
Profit	€, %	Yearly	$R_2 - R_8$

through the given contractual agreements. However, the adjustment of demand (given a potential increase through lowering the price) can only be negotiated when the actual cost of the remanufactured product is clear, which is when the business case calculation is drawn by the end of the year. Thus, T_2 is at least one month for R_4 and can go up to a year for R_2 and R_3 (considering a coupling of supply and demand as established in the contractual agreement). This lack of information towards business-related information also impedes long-term decision-making towards resource allocation such as machine investments or training for remanufacturing operators. As the remanufacturing facility is an OEM, the key findings of the RPPC can be reported to the original R&D department to be considered for future remanufacturing projects.

As shown in the previous elaboration, the conceptual framework helps to identify RPPC challenges systematically. We assess the RPPC performance of the OEM remanufacturer on a low to medium level, especially driven by the availability and consistency of information. These factors coupled with the tracking period leads to a moderate to high level of impact caused by uncertainty on the process-level.

Suggestions for OEM remanufacturer

To increase the viability of the shown OEM remanufacturer, we derive certain suggestions based on the structured analysis of the conceptual framework. Firstly, it is very visible in the shown planning horizons (weekly, monthly, and yearly) that the data availability particularly on the process-level is very limited, thus, data availability depicts a major constraint for decision-making. With process-related information transparency, decisions towards resource allocation, process scheduling or production planning and control can be taken more effectively. While the operational data in the later process steps are tracked in real-time already, the manual input of bulk data with one to two weeks delay should be avoided. A possible solution could be a restricted interface for manual operators that tracks the status of the respective process after its finalized process step. By that, the information regarding each remanufactured core would be entered in a data base. In that way the root cause of the identified failures could be traced to certain shifts or operators. Here, a Poka Yoke approach should be used for easy accessibility to reduce input failures to a minimum, considering the high fluctuation of the human operators.

When a sufficient data availability on the process-level is implemented, tracking the lead time on process-level should be established to measure the incremental and overall performance of the system. This could also potentially reveal bottlenecks that require strategic intervention such as capability enhancements for machines or operators.

The lead time is not just dependent on the FR of the process-level, it is also impacted by the demand and supply of cores as well as their remanufacturability. Hence, the implementation of a forecast based on historical (sales) data as well as the consideration of uncertainty quantification for R_2 to R_4 are vital for a more accurate RPPC. As the current safety stock is determined by assumption, the incorporation of a real-time data availability at time t, a calculated lead time on process-level, and forecasts for the system-related FR, effective minimum and maximum level for safety stock of components and spare parts can be calculated. This would additionally enhance the system's performance as it can be either more flexible regarding production changes, or reduce the existing working capital within the remanufacuring plant.

Finally, based on all of the proposed adjustments, we suggest a profit and loss (i.e. cost) calculation at least on a monthly basis. This sets the foundation for strategic investment decisions but also for sound customer negotiations regarding the pricing of cores or remanufacturing products. In the case of the OEM remanufacturer, we also suggest frequent feedback streams of the remanufacturing department to the original R&D to enhance the design for remanufacturability for future remanufacturing products based on real-world observations.

Discussion

In this research paper we embarked on the definition of functional and non-functional requirements for RPPC as foundational pillars to tackle the existing complications in the field. The generic structure of the conceptual framework allows academic scholars and industrial decision-makers to design feasible remanufacturing systems, and to evaluate remanufacturing performance systematically.

Despite the advancements in the field of remanufacturing and its inherence in circular business models, real-world RPPC systems continue to face challenges in managing uncertainty, as the OEM remanufacturer exemplifies. Avoiding or neglecting uncertainty on the system- and process-level leads to major inefficiencies in remanufacturing operations that result in increased production costs. The distinction of uncertainty into its different types (i.e. uncertain supply or uncertain remanufacturability) and their association with the FR among the NFR depicts the starting point in its mitigation strategy. Both uncertainties may complicate RPPC systems but the approach to tackle these issues differ heavily. Especially considering the KPIs for performance evaluation taking the uni-direct relationship between the RPPC system performance and the impact caused by uncertainty into account. This is particularly the case for process-related FR, as the uncertainty on the process-level and its implied impact is caused by in-transparent processes or its associated information. This means that a sufficient RPPC system with real-time feedback control can reduce process-level uncertainty for R_5 to R_8 to an absolute minimum.

The elaboration of this finding represents a novel approach in remanufacturing literature with vast implications in the field of RPPC. It is vital that process transparency should be emphasized as one of the main drivers for efficiency. As many remanufacturing facilities rely on traditional RPPC solutions, the incorporation of data driven control systems in the form of digital twins [20, 52] illustrate an effective method for industrial decision-makers.

Based on the findings of this conceptual research paper, recommendations for further research arise. The current structure of the framework and the RPPC system is limited to qualitative consideration regarding performance measurement and the implied decisions, as outlined in Subsection "RPPC system". The structure of the RPPC system corresponds to a mathematical model that takes the information of the respective FR and existing NFR at time t in consideration to take decisions. With a sound examination of the KPIs in Table 1 (both qualitative and quantitative) a quantitative mathematical model can be established. In this context, uncertainty quantification (UQ) offers a valuable approach utilizing historical data, trends, and forecasts for a more accurate account of the inherent uncertainty. The incorporation of UQ at the KPI-level could be beneficial, providing specific measures for each KPI to allocate the impact caused by uncertainty accordingly. However, as Hoffmann & Knorn [14] show, centralized optimization models are subject to judicious simplifications to be computationally feasible. For that reason, a distributed or decentralized decision-making approach regarding the FR and the RPPC system could be considered. Based on the findings of our work, this approach could further develop the evaluation and optimization of RPPC systems.

Conclusions

This research paper developed a conceptual framework for requirement definition of RPPC. This includes the definition of eight FR, namely design for remanufacturability, demand of remanufactured products, supply of cores, remanufacturability of cores, traceable value stream processes, human workforce, production assets and tools, and safety stock of components. These FR are essential for RPPC; for performance measurement of the system we associated a total of 48 KPIs with the respective constraints and types of uncertainty. We merged all these concepts into the coherent conceptual framework for requirement definition of RPPC, considering the time-dependent relationships among the FR, and drawing a unidirect relationship between the system's measurable performance and the impact caused by uncertainty. While there is an inherent level of uncertainty in RPPC systems, the conceptual framework helps industrial decision-makers to identify the specific uncertainties regarding the FR, and thus, develop mitigation strategies such as data-driven forecasts or process visibility.

The current structure of the conceptual framework is limited by a qualitative RPPC system. For the further development of the field, we aim to transform the conceptual RPPC into a quantitative model for system optimization.

While we set a particular focus on economic performance measures, environmental KPIs and their implications on the RPPC system could be also considered. This is especially important under new government regulations, where carbon emission reductions can be factored into economic considerations.

Appendix

In this Appendix, the NFR (i.e., KPIs) for RPPC are described and calculation formulas (if existent) are outlined.

- Number of managed BOMs [10]: The number of managed BOMs depicts the number of BOMs are considered in remanufacturing operations regarding the respective product types and variants. This KPI is particularly important for contract and OEM remanufacturer that have access to these information.
- Number of concessions [10]: The number of concessions measures the amount of validated requests to the OEM regarding component design modifications to increase component reuse and salvation. An increase of this KPI could hint towards a loss in quality.
- Design parameter entropy [37]: The design parameter (DP) entropy depicts the average entropy of all DP for the FR on a remanufacturing product design level. DP could encompass attributes such as the structure, color or label in dependence of the customer requirements; here, S depicts the entropy of the respective DP i, with $i \in [1, k]$:

$$S_{\mathrm{DP}} = \frac{1}{k} \sum_{i=1}^{k} \mathrm{DP}_i . \quad (2)$$

- Function entropy [37]: The function entropy (FE) measures the entropy in the design phase regarding the fulfillment of DP corresponding to the FR of the product, in dependence of the customer requirements. Here, i is the number of FR assigned to the DP; n is the number of DP associated with the FR[2].

$$S_{\mathrm{FR}} = - \sum_{i=1}^{n} \mathrm{FR}_i \ln \mathrm{FR}_i . \quad (3)$$

- Remanufacturability [34]: The remanufacturability as a design for remanufacturability KPI depicts a decision-making tool based on fuzzy models regarding technical, economic, environmental, and resource dimensions. Each fuzzy model is based on a number of qualitative and quantitative remanufacturing factors such as the remanufacturing processes, associated costs, environmental implications or salvation rates.
- Availability of data: The availability of data is concerned with the available information regarding the respective FR R_2 to R_5, R_7, and R_8. Here, the dype of information differs among the different requirements; however, a sound data foundation is essential for effective RPPC. For that reason, the availability of data measures the time difference between the required information for KPI-based decision-making.
- Forecast accuracy [31]: The forecast accuracy measures the reliability and performance regarding the forecasted FR R_2 to R_4. An evaluation of this KPI is essential to assess discrepancies between the predicted and actual demand, supply and quality.
- Demand backlog [2]: The demand backlog depicts gap between the customer demand requirements and the shipped remanufacturing products. This KPI helps remanufacturing enterprises to assess their production capabilities and identify bottlenecks in their processes. For that reason, the demand backlog can be further distinguished into the assembly or disassembly backlog that is necessary to fulfill the customer demand. As the backlog may lead to contractual penalties, the backlog should be minimized.
- Shipment of products [2]: The shipment of products measures the number of actually shipped remanufacturing products to the final customer. Together with the demand backlog this KPI identifies whether the demand can be fulfilled under the current capability constraints.

[2] The FR in this KPI depict FR that are based on customer requirements in the design for remanufacturability process. Thus, they do not refer to the FR for RPPC.

- Demand delivery delay [2]: The delivery delay is concerned with the shipment of products and their occurred delay to fulfill the customer demand. Similarly to the backlog demand, the delivery delay should be reduced to a minimum.
- Product cannibalization [1]: The product cannibalization refers to the market erosion of the new product by introducing the remanufactured product into the market. Hence, this KPI measures the impact on the traditional business due to introducing the remanufacturing business.
- Supply delivery delay [4]: The supply delivery delay corresponds to the discrepancy between agreed core supply and actual core supply. This KPI measures the performance of the respective reverse logistics provider and helps for an accurate RPPC. Similar to the demand delivery delay, the delay of the supply should be tracked and minimized; contractual penalties could optimize supply delays from the reverse logistics partner.
- Core / product ratio [10]: The core / product ratio (CPR) measures the average number of cores used to produce one remanufactured product. This KPI aims to minimize the number of cores and components necessary to remanufacture products with a target number of one. For the calculation of this KPI entails the processes cores C, the shipped products P, the WIP, and the level on stock S:

$$CPR = \frac{C}{P + WIP + S}. \tag{4}$$

- Core class distribution (CCD) [10]: The CCD assesses the spread of cores in stock by associating the value of the cores according to a dedicated core class, naming A, B, C with a descending grading. The rationale of this KPI is to improve WIP and value of cores in stock. The target of this KPI is to approach the number 1. The formula entails the number of assessed core C_i with $i \in \{A, B, C\}$, multiplied with the assumed value of that core class, and the total number of cores n:

$$CCD = \frac{C_A + 0.3C_B + 0.15C_C}{n}. \tag{5}$$

- Product salvage rate (SRP) [10]: The product salvage rate measures the percentage of reused components in a product, a product variant, or a product type to measure the remanufacturing success rate. The notion i refers to the specific product with $i \in [1, n_i]$ and j with $j \in [1, n_j]$ to the specific component; r depicts the the value of the respective component with respect to the total product costs:

$$SRP = \sum_{i,j} r_{i,j} SRP_{i,j}. \tag{6}$$

- Component salvage rate (SRC) [10]: The component salvage rate measures the percentage of components or sub-assemblies salvaged. This KPI helps to identify remanufacturability and turnover for inventory optimization on a product level. Here, j refers to the respective reused core component R with a total number of n components:

$$SRC = \frac{R_j}{n}. \tag{7}$$

- Core disposal rate (CDR) [10]: The core disposal rate refers to the mass of core components that are not salvaged for remanufacturing.
- BOM compatibility [56]: The compatibility of BOMs refers to the degree of compatibility among the remanufacturing products, including the product type and variant compatibility. The BOM compatibility is particularly relevant for OEM remanufacturers as they

have access to these information; the analysis can be shared and discussed with the R&D department to improve remanufacturability in the future.

- Cycle time [10]: The cycle time depicts the required time from the beginning to the end of a process p. The cycle time can be measured for a specific process step or the whole remanufacturing process.
- Lead time [10]: The lead time depicts the real time that one product or component needs for a specific process, or the whole remanufacturing operations. Aside from the current cycle times, this KPI includes delays, waiting times or time on stock.
- Failure rate [49]: The failure rate depicts the rate of failures for a specific product, process, or resource over a certain time t. This KPI helps to track the performance of specific parts of the system over a time period T with $t \in (0, T]$.
- Remanufacturing costs: The remanufacturing costs depict the sum of all costs for the remanufacturing operations. The remanufacturing costs can be further distinguished into different cost classes such as fixed costs or variable costs, or specified into core, product, process, or resource costs. Additionally to these operational costs, costs for acquisitions or other investments could be relevant to consider for strategic decision-making. Overall, the costs are measured over a time interval t with $t \in (0, T]$.
- Remanufacturing profit / margin: The remanufacturing profit measures the profitability of the remanufacturing system. This KPI is essential to measure the overall performance of the RPPC system. Here, it is vital to measure which product types and variants create the highest turnover to plan the processes accordingly. Similar to the costs, the profit is measured over a time interval t with $t \in (0, T]$. The remanufacturing margin represents the proportion of the remanufacturing profit to the created revenue of sold products.
- Process digitization [20]: In contrast to the performance-oriented KPIs such as the product salvage rate, lead time, or the remanufacturing costs, this KPI measures the degree of digitization within the remanufacturing plant, particularly the process digitization. The digitization degree is highly associated with the data availability, and thus, helps to mitigate the impact caused by process-related uncertainty. Here, the time between an action or a decision and the implementation into the system is crucial.
- Personnel saturation [10]: The personnel saturation represents the proportion of human operators that are needed to work on a particular product or machine to cover all required operations and skills.
- Hours per unit [10]: The hours per unit represent the workload in time to product one unit of product.
- Work in progress (WIP) [10]: The work in progress depicts the cost of cores and core components in product. The value of this KPI depends on the already completed processes, including the costs of labor, machining, and overheads.
- Original equipment effectiveness (OEE) [10]: The original equipment effectiveness measures the manufactured output of machines and production equipment based on the process availability, efficiency, and quality.
- Process and product versatility: The versatility depicts a KPI that is concerned with the compatibility of resources such as human operators or machines towards the remanufacturing of products and processes. Due to the different remanufacturability states and the arriving core variant, a high versatility is crucial. As most machines are only suited for specific processes (e.g., disassembly or cleaning), this KPI is particularly important for human operators in remanufacturing.
- New component cost (NCC) [10]: The new component cost is concerned with the purchasing price of new components within the remanufacturing process. This KPI is particularly important for an optimal inventory level and as an indicator for remanufacturability.

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Declarations

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