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Integrating ReMake DPP and Remanufacturing Decision Engine to enable the next wave of SME remanufacturers

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Abstract

Remanufacturing provides significant economic and environmental advantages but its scalable implementation particularly among small and medium-sized enterprises (SMEs) is subject to a variety of challenges. The most predominant ones are the insufficient access to comprehensive product-related information and the inefficiencies in their operations that result out of this gap of knowledge. Furthermore, the lack of financial resources, infrastracture and skilled labour complicates the adoption of remanufacturing by SMEs. This paper addresses these challenges by integrating the ReMake digital product passport (DPP) that provides valuable end-of-life (EOL) information about the arriving products with the remanufacturing decision engine (RDE) that utilizes product and process information to improve remanufacturing system performance. This represents a novel approach to enable SMEs to overcome the uncertainties inherent in circular business models but also enhance their profitability. The feasibility of the developed concept is evaluated in a conceptual case study with a SME remanufacturer of industrial coffee machines. The open-source model is easily applicable and follows a low-cost approach with limited IT infrastructure requirements; thus, this approach has the potential to enable the establishment of SME remanufacturers globally.

Keywords: Remanufacturing, Digital Product Passport, SMEs, Circular Economy, End-of-Life Decision-Making, Optimization Framework, Data-Driven Manufacturing

1. Introduction

The scarcity of critical raw materials and the drive towards sustainability are heightening the focus on the circular economy and its associated R-strategies [1]. This is compounded by increasing governmental regulations compelling

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industrial companies of all sizes to adopt sustainable practices [2]. Particularly within remanufacturing, an established market exists where Small and Medium-sized Enterprises (SMEs) source end-of-life parts and reintroduce them to the market [3, 4]. This requires vast experience and knowledge regarding the respective original equipment (OE) products within specific industries [5]. While larger enterprises often possess dedicated research and development (R&D) teams to identify the necessary products, components, and technologies for remanufacturing, SMEs typically lack these capabilities [6]. This challenge is intensified by shortening product lifecycles from Original Equipment Manufacturers (OEMs) and the rising complexity due to electrification. This presents a significant entry barrier for SMEs wishing to adopt remanufacturing and other circular economy strategies, as effective decision-making necessitates detailed knowledge of the EOL product and its requisite production processes [7].

Beyond the lack of product-related information, remanufacturing and other circularity-oriented production systems demand specific attention to their effective production planning and control; consequently, qualitative and quantitative optimisation methods employed in traditional manufacturing are only partially applicable in this domain [8]. This can further impede the viability of SMEs, as they often lack the specific experience and capabilities to apply these complex methods effectively.

The Digital Product Passport (DPP), spearheaded by the European Union's Ecodesign for Sustainable Products Regulation (ESPR) [9], offers an approach to address the complications arising from this information deficit. The DPP aims to bridge the information gap concerning components, materials, chemical substances, repairability, and appropriate disposal methods documented by OEMs, for stakeholders involved in a product's EOL [10]. However, a significant challenge persists: stakeholders providing OE information may face disadvantages—such as compromised business integrity, diminished customer reputation, or reduced aftermarket share—rather than accruing benefits [11]. Furthermore, collecting and preserving this information necessitates complex technologies and robust data infrastructures [12]. Nevertheless, the DPP concept offers the potential to optimise choices across product design, production, use, and disposal collaboratively, thereby holistically enabling product circularity [10]. Given that insufficient information and know-how are major hurdles for SMEs adopting CE strategies [13], the DPP could lower entry barriers and empower new entrants in the market for product circularity, effectively extending product lifespans.

Currently, the DPP is largely restricted to product-related information aimed at enabling circularity at the product level. A predominant challenge for circularity-oriented business models, however, remains operational inefficiencies, which contribute to increased production costs [8].

This research aims to bridge this gap by integrating the ReMake DPP [14] with an innovative Remanufacturing Decision Engine (RDE). This integration establishes a framework enabling remanufacturers to utilise open-source, data-driven optimisation techniques for enhancing performance via standardised DPP data. Such an approach is particularly advantageous for SME remanufacturers, who often lack comprehensive product-specific information and the technological expertise required to leverage this data for operational efficiency. The open-source nature of the proposed system is intended to promote circular business growth within the EU, with a specific focus on SME remanufacturers.

This paper focuses specifically on remanufacturing, acknowledged for its high value retention among circular economy strategies that extend product lifespans. This emphasis is due to remanufacturing often encompassing other strategies such as reuse, repair, and refurbishment.

2. Literature review

2.1. *Retaining product value through remanufacturing*

To enable a sustainable production and consumption, one major development that aims to combine economic viability, environmental consciousness and social justice is the paradigm of the circular economy (CE). Driven by resource scarcity and environmental pollution, the CE aims to reduce landfill by reintroducing products and its composed material back into the original product life-cycle in a closed-loop system. This paradigm can be distinguished in 10 different 'R' strategies that aim to reduce the waste of resources by smarter product use and manufacture (i.e., refuse, rething, and reduce), extend the lifespan of product and its parts (i.e., reuse, repair, refurbish, remanufacture, and repurpose), and the useful application composed materials (i.e., recycle and recover) [2, 1]. [1] Since remanufactured products have a higher value than the ones that are reused, repaired or refurbished, this CE strategy possesses the highest business potential [3].

In contrast to the other strategies, the remanufacturing process is rather standardized; it consists of the visual inspection and diagnosis of the old part, disassembly, cleaning, rework and reconditioning, assembly, and final testing [5, 15]. Despite its standardized process routing, remanufacturing is subject to a variety of uncertainties and complications that impede its production planning and control; these uncertainties include the supply and quality of the core (i.e., old parts after the end of their life) and the customer demand [8]. This is particularly critical as the combination of these uncertainties may either lead to high stock levels that bind required resources or costs of lost demand. Due to the lack of investment capabilities, remanufacturers highly rely on human labour that is prone to errors and less reliable than automated [4]. Especially handling failures that result in higher scrap rates have a high impact on the throughput and effectiveness of remanufacturing systems [16].

2.2. *Challenges for SMEs to adopt remanufacturing*

When adopting remanufacturing, literature and industrial practice distinguish between two types of remanufacturers: original equipment manufacturers (OEM), remanufacturers and independent remanufacturers. While the OEM remanufacturer possesses the information from the series line such as production data, bills of materials (BOMs), and information regarding the product's initial quality and field performance, the indepedent remanufacturer is not associated with the OEM and thus, can only access the information that are available on arriving core level [8]. As the OEM is mostly a large corporation, we assume that the SME remanufacturer face the typical challenges of the independent remanufacturer.

These SME remanufacturers are subject to a variety of complications. According to Kondala et al. [13], SMEs do not have the capabilities to easily adopt changes in their strategy towards a circular business models due to a lack of performance measures, financial resources, technology and innovation, and know-how. While certain remanufacturing products require only small financial investments (i.e., products with manual process execution), innovation and technological expertise are vital [6].

One major impediment for SME remanufacturers is the accessibility of product-related information on core level. This includes the quality of the arriving core and its components, the composed raw materials, its assembly technologies, the product variant, and relevant lifecycle information that could benefit the remanufacturing process [14]. Without this data, the cost and the complexity of the remanufacturing process increase significantly [8]. This not only affects the production cost of the remanufacturing product, according to Tolio et al. [4] this leads in a lower product quality which results in a lower competing price.

Aside from the lack of information availability, SMEs lack the capabilities fully utilize their existing data to take informed and optimized decisions due to knowledge gaps [13]. This fact is highlighted by Fatimah et al. [7], where Indonesian SME remanufacturer lack infrastructure and knowledge to take informed and data-drive decisions to optimize their system's performance. In contrast, there is a research gap regarding optimization models targeting specifically SME remanufacturers as existing approaches mostly require a high degree of information depth and accuracy [17, 18]. Here, only the EOL decision-making model developed by Hoffmann and Knorn [19] has low requirements towards computational capacity and information availability, and thus, could be beneficial for SME remanufacturers.

2.3. *Digital Product Passport*

A promising way to address information accessibility issues for SME remanufacturers is the adoption of Digital Product Passports (DPPs). DPPs act as a digital identity card for products, components, and materials entering the EU market. It aims to contain relevant information that improves sustainability, fosters circularity, and reinforces legal compliance [9].

[1] Under specific circumstances repurpose possesses similar potentials regarding its lifespan extension. However, in most cases remanufacturing is a prerequisite before a product is repurposed.

When implemented, this regulation will enable a DPP ecosystem comprising of various actors and services collaborating together to deliver product data [20].

The DPP will comprise of two main elements: a standardised DPP System and customisable DPP Data Models. The DPP System will be standardised to promote service development and improve functionality, while the data models will remain flexible to accommodate industry-specific needs or delegated activities. The standardisation of the system is expected to foster a strong service ecosystem, providing substantial value to remanufacturing SMEs.

Research continuously underscores the transformative impact of DPPs on sustainable manufacturing by enhancing decision-making and minimising manual procedures in remanufacturing, facilitated by readily accessible data [21, 22]. The advantages of a DPP for SME remanufacturers are significant. This encompasses a reduction in uncertainties concerning core availability and quality, as well as the prompt identification of non-remanufacturable components, hence conserving significant time and resources [23]. However, despite these benefits current DPP data models are not designed for remanufacturing use cases, and this is where NMIS-led ReMake DPP is designed to address this challenge.

3. ReMake DPP RDE

3.1. Rationale of ReMake DPP RDE for SMEs

The ReMake DPP RDE depicts a novel approach that integrates the ReMake DPP [14] built on standardised DPP system and the remanufacturing decision engine (RDE) into one coherent architecture to optimize remanufacturing decision-making. The model is generally applicable but specifically developed to enable the next wave of SME remanufacturers. It aims to bridge the information and knowledge gap by providing the product-related information that are stored in the ReMake DPP and utilizing them in the RDE. A high-level data and information flow of the ReMake DPP RDE is illustrated in Figure 1.

The backbone of this architecture is the ReMake DPP which stores the most important information regarding the incoming core. Based on the information gathered when inspecting and diagnosing the core, the available data in the DPP, and the knowledge base of that SME remanufacturer, the RDE processes these incoming information to enhance decision-making.

For instance, one of the complications that have been mentioned in literature regarding SME remanufacturers is the lack of performance measures [13]. Thus, the RDE could incorporate different key performance indicators (KPI) specifically tailored for remanufacturing processes (e.g., Graham et al. developed an overview of different KPIs to measure remanufacturing performance [24]). Furthermore, the adoption of other CE strategies requires a high degree of technological expertise [7]. However, with the right information available, the RDE can close that knowledge gap. For example, when a part flagged as high corrosion risk in the DPP, this part may either be routed to recycling instead of remanufacturing to avoid customer claims, or a new coating process that prevents corrosion might be established; both possibilities can be taken in consideration based on their profitability, risk, and the overall aim of the SME remanufacturer. The different data layers and connections as well as the applicability of the RDE are in-depth elaborated in the following subsections.

3.2. Overview of ReMake DPP model

While current DPP initiatives demonstrate a clear commitment to traceability, compliance, and end-of-life issues, a critical review of their data models uncovers an apparent research gap: their inadequate ability to address the particular challenges encountered by SME remanufacturers[14]. Current DPP implementations, are either sector-specific solutions like the Battery Passport or lack the necessary detail and unique data properties required to optimise remanufacturing processes.

The ReMake DPP aims to address this gap by creating a data model designed specifically for remanufacturing, facilitating effective data sharing throughout the product lifecycle. This approach goes beyond traditional DPPs by highlighting data attributes essential for extending product life through remanufacturing. The ReMake DPP model, detailed in Table 1, highlights several key data categories, including product identification, material composition, remanufacturing process requirements, and quality requirements through use of MBD/QIF files.

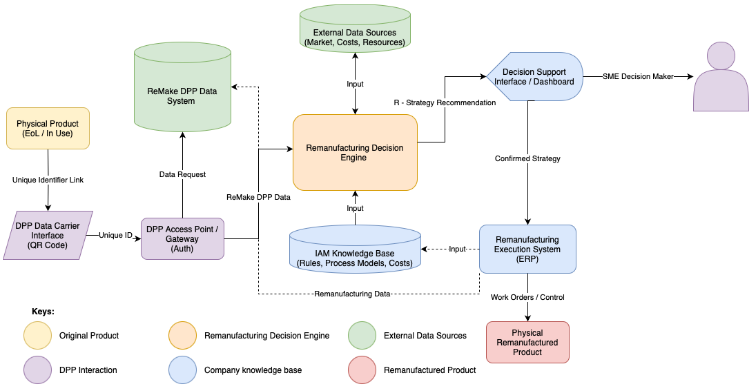

Fig. 1. ReMake DPP RDE architecture

Table 1. Data for Digital Product Passports (DPP) in Remanufacturing [14]

Data	Description	DPP Rationale
Identification	Product manufacturing number, e.g. GTIN	Enables detailed product traceability
Product Status	Product status - e.g. End-of-Life	Assists in assessing remanufacturing demand
Product Data	Product category, description, use case, manufactured/shipment date, life cycle	Supports remanufacturing certification and compliance with OEM standards
Digital Twin	Simulation models or IIoT integration models based on AAS	Provides in-service data for process optimisation and decision-making
Warranty	Original Warranty period	Helps determine appropriate warranties for remanufactured products
Material Data	Material ID, standard and other information	Supports End-of-life (EoL) decisions and material reuse
Remanufacturing data	Remanufacturing processes, cost models and defect management	Provides critical data for remanufacturing operations
Skills	Skills, training paths, certification (3^{rd} party), and resources	Remanufacturing is predominantly manual; this data supports workforce planning and investment in talent
Waste Prevention & Collection	Guidelines on waste prevention & collection points	Supports circular economy objectives by minimising waste and data on collection points
Quality Requirements	Quality documents & MBD/QIF	Ensures remanufactured components meet Class A remanufacturing standards (DIN SPEC 91472)

3.3. *Remanufacturing Decision Engine*

Unlike other academic approaches that aim to develop the best model to solve a specific problem, the remanufacturing decision engine rather combines these developments and makes them accessible for SME remanufacturers. With that, the RDE aims to close the knowledge and capability gap that prevails in SMEs to enhance their decision-making regarding performance measurement, operations, procurement, or other fields where these companies lack expertise.

The foundation of these decisions are the product-related information (i.e., information that is gathered when the core is inspected and those that can be drawn from the ReMake DPP) and the process-related information of the SME

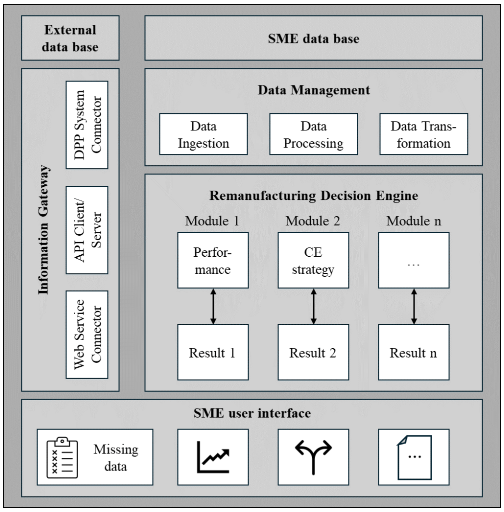

Fig. 2. RDE architecture

(i.e., data about the current production planning, machining capacity, qualification profiles, etc.). The models incorporated in the RDE are based on these information and give solutions that the decision-maker of the SME can apply. When applying the ReMake DPP RDE, the SME remanufacturer requires an IT infrastructure with minimum requirements to store relevant product-related and process-related data. An information gateway to access these information is provided within the architecture of the proposed system to make it as accessible as possible. After the important information can be accessed, the data can be processed and transformed into the necessary structure to make use of them. An overview of the RDE architecture is provided in Figure 2. To exemplify the structure and functionality of the RDE, two modules are described that are based on academic findings regarding remanufacturing: the performance measurement engine [24] and the CE strategy engine [19].

3.3.1. Performance management

In Graham et al. [24], the authors reflected on a variety of KPIs that are relevant for general manufacturing systems and ones that are specific for remanufacturing. To exemplify the functionality of the RDE three KPIs that help to evaluate the performance of the SME remanufacturing system. The observed KPIs include:

1. Product margin
2. Core / product ratio
3. Lead time

The chosen KPIs evaluate the remanufacturer's performance from three different dimensions: the financial perspective, the remanufacturability perspective, and the overall process perspective. While the product margin measures the achieved profit for each serviced product, the core / product ratio evaluates the number of cores that are required to build up one remanufactured product. Lastly, the lead time evaluates the time that is needed to remanufacture one core to its like-new condition and service it to the customer.

As previously outlined, SME remanufacturers lack efficient measures to evaluate their system's performance. The defined KPIs by Graham et al. could be a beneficial addition to their operations. The most relevant KPIs for remanufacturing operations are stored with their calculation formulas in Module 1. In order to calculate the right measures, an interface shows to the decision-maker which values are relevant or missing. In the case of the three KPIs, the SME data base needs to provide the information such as the product cost and its selling price to calculate the product margin, the number of incoming cores and the number of outgoing products for the core / product ratio, and the overall time of the operations to calculate the lead time; these data should be provided over a defined time horizon (e.g., daily, weekly or monthly) to create the performance report. With that, the SME decision-maker can identify deviations over a longer time horizon or evaluate the overall performance of its remanufacturing system. Furthermore, with the data available in the DPP, product-related KPIs such as the core / product ratio can be distinguished more precisely into cores that did not fulfill the requirements for remanufacturing due to DPP information.

3.3.2. CE strategies

In Hoffmann and Knorn [19], the authors developed a mathematical model that distinguishes between remanufacturing and recycling decision-making on component-level, evaluating the viability of recycling as an alternative EOL strategy to remanufacturing. In contrast to many mathematical models in academic literature, the optimization approach requires low computational efforts and only a handful of information that the ReMake DPP provides and the RDE can utilize.

In this publication, the authors distinguish between remanufacturing and recycling based on the achievable profitability per processed part. For example, a component that is composed only of a single material (e.g., a housing part) can either be considered for remanufacturing involving its cleaning, reprocessing, assembly, and final testing, or its direct recycling. Considering an uncertain customer demand and fluctuating raw material prices, recycling might be a viable alternative, particularly to salvage existing capacities rather then leaving them unoccupied.

For this evaluation, a variety of product-related and process-related information are required. The product-related information are based on the core inspection and the available information in the DPP. This might include an overview of the composed raw materials as well as their weighted percentage. Additionally, the process-related information could refer to the production data (i.e., the actual cost of a component for remanufacturing purposes, its fall-out rate in the process, or the requested demands for this specific component variant) that can be utilized by the optimization model that is incorporated in Module 2. Similarly to the performance Module, data that is necessary to solve the optimization problem will be shown in the SME user interface to be provided in the SME data base. When all necessary data are available by the SME, the RDE calculates the component profitability to remanufacture or to recycle a component. The recycling-related information are provided by an external data base such as the current raw material stock market.

Here, the RDE salvages information from the internal data base, the ReMake DPP, and external information to provide a sound foundation for the industrial decision-maker to use certain components either for recycling or remanufacturing.

4. Case Study: Illustrating the ReMake DPP RDE Framework

To demonstrate the potential operational benefits of the proposed ReMake DPP RDE framework, this section details a conceptual case study. The study centres on 'WhiteGoods Reman Ltd', a UK-based SME specialising in the remanufacture of industrial coffee machines. WhiteGoods Reman Ltd. is characterised as a typical SME remanufacturer, an entity employing 25 personnel with deep knowledge of R-strategies.

4.1. Conventional Operational Challenges

In a typical operational scenario, lacking the integrated data and decision-support capabilities of the ReMake DPP RDE, WhiteGoods Reman Ltd. would confront considerable inefficiencies. Core assessment and remanufacturing processes would be heavily reliant on time-consuming manual inspections, tacit knowledge, and often extensive reverse engineering due to a lack of standardised product data. This operational model inherently includes several challenging and resource-intensive stages:

- Manual receipt, identification, and data logging for each incoming core
- Labour-intensive fault diagnostics
- Full disassembly for detailed physical examination and component-level assessment,
- Protracted reverse engineering efforts
- Consequently, elevated scrap rates and sub-optimal resource utilisation stemming from unanticipated component failures or incomplete initial core assessments.

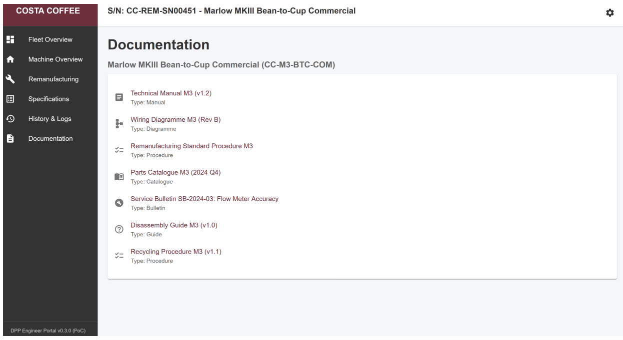

Fig. 3. Illustrative ERP interface showcasing accessible documentation (technical manuals, disassembly guides) sourced from the ReMake DPP for a commercial coffee machine module.

4.2. Conceptual Framework Implementation and Enhanced Operations

The introduction of the ReMake DPP RDE framework, incorporating a prototyped lean Enterprise Resource Planning (ERP) system designed for remanufacturing core management, is conceptualised to transform these operations.

Upon arrival, each core's unique identifier (e.g., a QR code linked to its ReMake DPP) would be scanned. The integrated ERP system would then automatically retrieve and parse the comprehensive, structured data from the product's ReMake DPP. This mechanism would furnish WhiteGoods Reman Ltd. with immediate access to critical information, visualised through dedicated ERP interfaces. Essential documentation, such as technical manuals, disassembly guides, and standardised remanufacturing procedures (see Figure 3), would become readily accessible, significantly reducing the reliance on tacit knowledge or reverse engineering.

Furthermore, a detailed Bill of Materials (BOM), including part numbers, average lifespans, and material specifications, alongside a comprehensive maintenance and repair history would be available.

4.3. Intelligent Decision Support via the Remanufacturing Decision Engine (RDE)

The structured and validated data collated within the ERP from the ReMake DPP serves as a robust foundation for the Remanufacturing Decision Engine. The RDE integrates this product-specific information with WhiteGoods Reman Ltd.'s internal operational context (technician skillsets, equipment availability, process costs) and pertinent external market data (demand for remanufactured units, secondary material values). This holistic data synthesis empowers the RDE to execute various decision-support algorithms, providing actionable insights.

4.4. Projected Operational Enhancements and Strategic Impact

The adoption of this integrated ReMake DPP RDE framework offers considerable potential for transformative change within SME remanufacturing operations. The immediate availability of accurate product data via the ReMake DPP and its management within a specialised ERP would substantially reduce reliance on reverse engineering and expedite core triage and processing. Subsequently, the RDE's capacity to provide data-driven recommendations would enhance decision quality regarding EOL strategies, resource allocation, and process optimisation. Collectively, these enhancements could lead to tangible benefits such as increased throughput, reduced operational costs, minimised waste, and improved quality of remanufactured products, thereby enabling SMEs like WhiteGoods Reman Ltd. to operate more competitively and sustainably within the circular economy.

5. Discussion

The introduction of DPP via the ESPR act marks a fundamental change in product lifecycle management in the EU. The legislation will facilitate informed customer choices and enhance transparency, but it will undoubtedly affect manufacturing costs and operational expenses for economic operators and remanufacturers. However, the standardised approach inherent in the DPP system generates unparalleled prospects for the remanufacturing sector, especially when integrated with the ReMake DPP data model and RDE architecture. With that, we close a vital gap in academic literature and industrial practice that aims to enhance the capabilities of SME remanufacturing companies considering their performance management , the evaluation of new business models, or their overall profitability.

The design of the ReMake DPP RDE presents a opportunity for researchers, organisations, and corporations globally to enhance the development of CE decision tool and share it with the whole ecosystem. This open platform enables everyone to develop specialised algorithms, decision matrices and business integration to support growth of remanufacturing. Researchers across EU can create decision algorithms customised for certain regional settings, regulatory frameworks, or industry sectors, all aligned with the standardised architecture enabled through ReMake DPP.

This collaborative ecosystem connects theoretical research with practical application, allowing SME remanufacturers with budget and skills gap to employ advanced decision-making tools to grow their business. The open-source characteristic of the RDE guarantees that advancements are advantageous to the entire remanufacturing community instead of being confined within proprietary systems. With that, we close a vital gap in academic literature but also academic practice.

In future the integration of the ReMake DPP RDE with advancements in generative AI and agent-based systems is predicted to transform remanufacturing processes. Through ingesting of structured data with standardised DPP and growing decision making tools, the self-governing agent-based AI systems could possess the capability to minimize decision-making durations from hours to minues, renahnce resource distribution, and reduce errors caused by human labour.

6. Conclusion and recommendations

This paper has introduced the ReMake DPP RDE framework, a novel architecture designed to address the persistent challenges confronting SMEs within the remanufacturing sector. By integrating a domain-specific Digital Product Passport for Remanufacturing (ReMake DPP) with a modular Remanufacturing Decision Engine (RDE), the proposed system offers a structured pathway to overcome significant disparities in essential product information and enhance complex End-of-Life (EOL) decision-making. The ReMake DPP component establishes a targeted data model vital for remanufacturing operations, while the RDE provides an accessible and open architecture for leveraging this data through diverse analytical modules. This bridges the gap between the raw product information and actionable operational intelligence for SME remanufacturers.

The illustrative case study demonstrates the considerable potential of this integrated framework to significantly improve SME‘s performance, mitigate operational uncertainties, and facilitate the adoption of optimal EOL strategies, favouring remanufacturing over less value-retentive alternatives such as recycling. Ultimately, the ReMake DPP RDE aims to lower entry barriers for SMEs, foster data-driven operational practices, and enable them to scale their remanufacturing activities profitably and sustainably. Further development and collaborative enrichment of this open architecture hold considerable promise for advancing the circular economy to support the next wave of remanufacturing innovation.

In the future, we aim to establish an open-source data model for the ReMake DPP RDE that considers additional optimization algorithms than those shown in this paper. We further want to create a low-cost ecosystem that different enterprises can salvage the provided strategies, establish new ones, and with that enable the establishment of new SME remanufacturers.

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