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Original
“Scale without mass”: A decision-making tool for scaling remanufacturing practices in the white goods industry / Franze', Claudia; Pesce, Danilo; Kalverkamp, Matthias; Pehlken, Alexandra. - In: JOURNAL OF CLEANER PRODUCTION. - ISSN 1879-1786. - ELETTRONICO. - Journal of Cleaner Production:417(2023), p. 138078. [10.1016/j.jclepro.2023.138078]

Publisher:
Elsevier

Published
DOI:10.1016/j.jclepro.2023.138078

Journal of Cleaner Production 417 (2023) 138078

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

“Scale without mass”: A decision-making tool for scaling remanufacturing practices in the white goods industry

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Remanufacturing
Circular economy
Waste management
Digital technologies
Digital platforms
Sustainability

ABSTRACT

Despite the well-known benefits of remanufacturing as a value recovery strategy for end-of-life products, its implementation is still highly industry-dependent and much more complex than traditional manufacturing. Digital technologies play a key role in overcoming the complexity that currently characterises - and at the same time limits - the successful large-scale implementation of remanufacturing activities. However, they can also engender new shortcomings in the implementation of remanufacturing activities, whose effects are not unidirectional or unambiguous. In this study, we explore how digital technologies can help overcome the shortcomings that prevent the scalability of remanufacturing activities in mature and complex industries which produce highly polluting waste. We conducted a longitudinal case study on the implementation of a white goods remanufacturing project that was launched in 2016 by a leading European distributor of spare parts for household appliances. Our results show that data centralisation – which creates efficiency at a local scale – does not guarantee the replicability of decision-making processes at a large scale; in fact, the opposite occurs. The study contributes to the circular economy and remanufacturing literature by unveiling the idiosyncratic shortcomings that are triggered by digitalisation, which limit the replicability of remanufacturing activities, and by proposing a decision-making tool that exploits platform logics in order to scale remanufacturing activities in mature and complex industries that produce highly polluting waste.

1. Introduction

The global trend towards sustainability highlights the current problem of reducing the impact of mature and complex industries with highly polluting waste, especially in developed countries where markets are saturated with huge quantities of new durable goods (Cardamone et al., 2021). The Circular Economy (CE) is considered an appropriate solution for waste management (Ellen MacArthur Foundation, 2013) because the concept aims to close the Product Life Cycle (PLC), minimise pollutant emissions, and maintain the maximum utility and value of products (Elia et al., 2017), thereby decoupling economic development from negative environmental consequences (Geissdoerfer et al., 2017). In March 2023, the European Commission (EC) proposed a number of new common rules to promote the repairing of goods, the so-called “right to repair”, which will result in savings for consumers and support the objectives of the European Green Deal by reducing waste, among others. Thus, certain companies may rearrange their business practices to conduct more repairs or even offer remanufactured goods (European Commission, 2023).

Among the various Circular Economy strategies, remanufacturing is considered an innovative approach that is environmentally preferable to other value recovery options (Charnley et al., 2019; Goodall et al., 2014). Remanufacturing is a form of a product recovery process that differs from other recovery processes in that it is a complete process: a remanufactured product should satisfy the same expectations of its customers as a new one (Nasr, 2019). It is the key to enabling a circular economy and has gained acceptance in the automotive, aerospace, communication, medical equipment, and white goods industry (D’Adamo and Rosa, 2016). However, its implementation is highly industry-dependent and much more complex than in traditional manufacturing (Abdulrahman et al., 2015), as the lack of standardised data and adequate information (e.g. on the location, condition or

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https://doi.org/10.1016/j.jclepro.2023.138078
Received 1 March 2023; Received in revised form 19 June 2023; Accepted 10 July 2023

quantity of end-of-life products) can lead to discrepancies, gaps and a lack of trust between actors in the value chain (Rossi et al., 2020). New technological solutions and management alternatives are crucial to reduce any shortcomings in the implementation of remanufacturing activities (Teixeira et al., 2022), but they are not always easily implemented at the technological, operational, and strategic levels (Lanzolla et al., 2021). On the one hand, digital technologies enable the enhancement of existing connections between objects, individuals, and organisations by complementing legacy skills with digital skills (Lanzolla et al., 2021). On the other hand, they also create new interdependencies that lead to higher levels of organisational complexity and an increasing level of substitution between legacy and digital domains (Lanzolla et al., 2021). Taken together, these tensions complicate the scalability of remanufacturing activities by adding the need to translate and codify the know-how required to effectively implement remanufacturing activities at scale to the well-known layers of technological and organisational complexity. Therefore, in this study, we have investigated the following research question: *how can digital technologies help overcome the shortcomings that prevent the scalability of remanufacturing activities in mature and complex industries that produce highly polluting waste?*

We conducted a longitudinal study on the white goods sector to answer this question. White goods are large home appliances such as refrigerators, washing machines, and tumbler dryers that were traditionally made in a ceramic white colour (hence the name "white goods"). The white goods industry represents one of the widest and fastest-growing sources of global e-waste (WEEE): in 2019, the world generated 53.6 million metric tons (Mt) of waste, with an annual growth of almost 2 Mt, which has been projected to grow to 74.4 Mt by 2030 (Forti et al., 2020). We conducted a longitudinal case study, within the white goods sector, on the implementation of "Second Life", a project for the remanufacturing and resale of end-of-life white goods that was launched in 2016 by a leading European distributor of spare parts for household appliances – hereafter Alpha.[1] The context in which Alpha implemented the Second Life remanufacturing project at a local scale can be regarded as a "revealing context in which to transparently observe" (Yin, 1994, p.40) the shortcomings that can impede the scalability of remanufacturing activities and understand how digital technologies can help to overcome them.

Our results show that data centralisation allows upstream remanufacturing activities to be made more efficient and to become optimised (i.e., "selection and collection" and "disassembly, cleaning, and inspection"), but does not guarantee the replicability of the large-scale decision-making processes of downstream activities (i.e., "repair, testing and cleaning" or "redistribution and resale"); in fact, the opposite occurs. The centralisation of data creates more organisational complexity by introducing new interdependencies between the knowledge that underlies such remanufacturing activities. This additional complexity makes the transfer and recombination of knowledge somewhat challenging and, together with the lack of incentives and strategic alignment of the stakeholders' interests along the supply chain, prevents the replicability of the remanufacturing activities at a large scale. Taken together, our evidence shows that to fully reap the technological efficiency benefits generated at a local scale and replicate them at a large scale, it is necessary to shift from traditional linear channel logics to platform logics based on circular and organic interdependencies between the different actors in the value chain.

Therefore, the study proposes the application of a decision-making tool - based on platform logic and data mining methods applied to a centralised database - whose aim is to make remanufacturing projects, such as Second Life, scalable, and to overcome the shortcomings that currently limit their replicability at a large scale. The study contributes to the circular economy and remanufacturing literature in three ways. First, starting from the shortcomings that are present in the implementation of the remanufacturing activities that are presented in the literature, the study provides empirical evidence on how digital technologies can help companies overcome such shortcomings. Second, the study unveils two new idiosyncratic shortcomings triggered by digitalisation and shows how they limit the replicability of large-scale remanufacturing activities. Third, the study proposes a decision-making tool that can be used to overcome these shortcomings by exploiting platform logics to scale remanufacturing activities in mature and complex industries that produce highly polluting waste, such as in the white goods sector.

The remainder of the paper is structured as follows: Section 2 provides an overview of the literature that underpins our investigation. Section 3 describes the research methodology. The results of the analysis are presented in Section 4 and discussed in Section 5, which also presents the decision-making model that can be used to scale remanufacturing activities. The study concludes with a summary of the main findings, the limitations, and research opportunities.

2. Theoretical Background

2.1. Remanufacturing potential and digital technologies

Among the several proposed CE strategies, remanufacturing is considered as an innovative approach that is environmentally preferable to other value recovery options (Goodall et al., 2014) as it preserves both the materials and the 'embodied energy' from the initial manufacturing processes and it allows considerable value to be retained from used products through the extension of the lifetime of a product (Charnley et al., 2019; Nasr, 2019). Such a strategy involves restoring a used product to a like-new condition (Matsumoto et al., 2016) through an industrial process composed of a set of sequential activities (Teixeira et al., 2022; Vogt Duberg et al., 2020); see Columns 1 and 2 in Table 1.

Remanufacturing introduces several triple-bottom-line benefits to the circular economy paradigm (D`Adamo and Rosa, 2016; Ovchinnikov et al., 2014). From an environmental perspective, it preserves the embedded value (energy, materials, and labour) that results from the efforts made when manufacturing new parts, thus avoiding the impacts of the production of new materials, along with their related energy-intensive mining, and of CO_2 emissions, and reduces the amount of waste generated at their the end-of-life (Jensen et al., 2019; Vogt Duberg et al., 2020). From an economic perspective, it reduces production costs, since secondary materials or recovered components are used (Bressanelli et al., 2021), thus protecting the industry against volatile material prices and supply disruptions issues (Boustani et al., 2010; Goodall et al., 2014). Finally, from a social perspective, it creates employment opportunities as it is a labour-intensive task (Farahani et al., 2019), and it also enables increased access to products/services for those people with low incomes, thanks to the lower purchasing prices of remanufactured products (Sitcharangsie et al., 2019; Zlamparet et al., 2017).

As conceptualised by Teixeira et al. (2022), such benefits are fostered by the implementation of digital technologies in the remanufacturing process, which becomes more efficient through a better management of customer relations (Cyber-Physical Systems, Big Data Analytics), real-time tracking and monitoring capabilities (The Internet of Things, Radio Frequency Identification), quality-dependent acquisition (The Internet of Things, Big Data Analytics), increased collection levels (The Internet of Things, Cloud Computing), and better-used product evaluation and remanufacturing (Augmented Reality, Virtual Reality, The Internet of Things, Collaborative Robots, Radio Frequency Identification, Data-Driven Simulation, Cyber-Physical Systems, Additive Manufacturing) (Teixeira et al., 2022). For instance, The Internet of Things and Big Data Analytics technologies can be combined to remotely locate and individually evaluate the end-of-life conditions of goods,

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[1] The company (Alpha) and its remanufacturing project (Second Life) have been anonymised for confidentiality reasons.

Table 1
Summary of the remanufacturing challenges that have emerged from our literature review.

Remanufacturing activities	Description of the activities	Challenges of the remanufacturing activities	References
Selection and collection	A discarded product that may be suitable for remanufacturing is chosen according to its quality, market value, and probability of being remanufactured, and it is then sold on the market for a second life as an easy and cheap replacement of components to avoid cases where the replacement of damaged parts could be too expensive. Discarded products are collected directly from the logistics centres by the company through the take-back system.	The need for an appropriate reverse logistics scheme.	*Thürer* et al. *(2019)*
		Uncertainty in the timing, qualities, and quantities of returned products leads to variable lot sizes.	*Gallo* et al. *(2012)*
		The condition of returned products and parts is usually unknown until they are disassembled and inspected.	*(X. Wang* et al., *2018)*
		The unpredictable conditions of the end-of-life product, supply and demand also make production planning and control problematic.	*Butzer* et al. *(2016)*
Disassembly, cleaning, and inspection	A product is taken apart into its components to identify what parts are reusable and which need replacing. The components are then cleaned and inspected to identify the reusable parts and decide whether to replace non-reusable parts with new ones.	Reverse engineering is frequently necessary for third-party companies to determine the specifications and characteristics of products, due to a lack of standardised data, thus making disassembly a labour-intensive task.	*Sundin and Bras (2005)*
		Disassembly and inspection require technically skilled engineers and technicians with ad hoc experience.	*(Siew* et al., *2020*; *Yang* et al., *2018)*
Repairing, reassembly, and testing	Components and parts are fixed or replaced and then reassembled. A final testing is performed in the same test cells that are used to manufacture the new product to ensure that it meets the required performance and quality standards.	Manual repairing is a highly labour-intensive and not repetitive activity, as the products arrive in unpredictable conditions that vary from case to case.	*Siddiqi* et al. *(2019)*
		Production planning and control difficulties make inventory management complicated, and the unknown conditions of the products lead to variable processing times.	*Butzer* et al. *(2016)*
Redistribution and reselling	The remanufactured product is sold to customers as a new product (which includes a warranty and after-sales service) but at a lower price.	The definition of quality assurance depends to a great extent on the quality of the received end-of-life product and it is difficult to obtain as there are no established definitions or standards for remanufactured products in various sectors.	*(Ondemir and Gupta, 2014*; de Vicente Bittar, 2018)
		Customers might not be convinced of the value of remanufactured products or unwilling to pay a price similar to that of a new product for a remanufactured product.	*Yang* et al. *(2018)*
		When independent remanufacturers rather than OEMs execute remanufacturing, there is no information sharing between them and no incentive to do so or to create a collaborative environment.	*Matsumoto* et al. *(2016)*

which in turn leads to an enhanced supply and demand matching and a quality-driven end-of-life acquisition strategy. The "digital product passport", proposed by the EC to create more environmentally sustainable and circular products, is highly innovative in this field: in the future, manufacturers will have to report, for example, on the recycled content, remanufacturing and recycling, and on the carbon and environmental footprints related to their products (European Commission, 2022). Therefore, the question is not whether manufacturers will move in the direction of such EC strategies as remanufacturing but rather when this will take place.

Two main issues have emerged from our literature review: i) the challenges associated with remanufacturing process activities; ii) the theoretical and technological limitations of the digital transition of this process.

Column 3 in Table 1 shows the challenges and barriers to the effective implementation of remanufacturing activities that have emerged from our literature review (i). These issues are related to the acquisition, collection, evaluation, and reprocessing of discarded products, which may result in poor forecasts of incoming end-of-life products (and spare parts), their quality, and the difficulty of matching supply and demand (Teixeira et al., 2022). Taken together, these challenges may hinder the adoption of remanufacturing at a large scale (Linder and Williander, 2017). Indeed, a remanufacturer requires a considerable amount of knowledge and data about both the WEEE before it can be processed and the product components before some of them can be repaired or remanufactured (Wang and Wang, 2019). However, the conventional WEEE remanufacturing method does not provide an effective communication and management approach. On the one hand, a large portion of the information on a product's lifecycle is lost during the product development and manufacturing stages (Kurilova-Palisaitiene et al., 2018). On the other hand, the data stream is also interrupted after the product is sold to the end user. Thus, WEEE collectors and remanufacturers need to rework and recreate the life-cycle information by themselves through different channels and different methods (Wang and Wang, 2019).

Apart from the challenges associated with remanufacturing process activities, several theoretical and technological limitations currently hinder the digital transition of remanufacturing processes (ii). There is currently no shared consensus about the standards and definitions of remanufactured products in various sectors (Yang et al., 2018). However, it is common sense that remanufactured products should be treated in the same category as "new produced" and that the guarantee should remain the same. Moreover, just like IoT/ICT standards, the data formats and the scope of application in remanufacturing are limited, and there are no methods to integrate heterogeneous data (Charnley et al., 2019). Moreover, since there are no standard solutions and limited demonstrations or applications of the data-driven simulation (Goodall et al., 2014; Okorie et al., 2020), its implementation in small-and medium-sized remanufacturing companies remains challenging (Lu et al., 2019). Finally, as we are currently witnessing a digital transition and many durable products have not been designed to be digitally compliant, there might even be a lack of even the simplest tracking technologies (Dawid et al., 2017).

2.2. *Remanufacturing as part of cascading product life cycles*

In order to include digital technologies, it is necessary for remanufacturing companies to address the whole circular economy and to take into account the product life cycles (PLC). The release of the circular economy strategy by the European Commission (EC) in 2015 increased the awareness of the necessity of a more sustainable use of resources, even though recycling technologies and industries were already an integral part of the market systems in that period. As described by Kalverkamp et al. (2017), reuse and recycling transactions are fundamental for a functional circular economy, and they regularly form some sort of cascade utilisation (Kalverkamp et al., 2017). There may be several cascade levels (reuse, recycle, recover) within a PLC, where the waste streams of products, components, and materials are separated. Certain streams remain at specific levels for lifecycle iterations, while others divert towards alternative lifecycles. At this point, the complexity of cascading clearly emerges, since it is either material or component oriented and could enter into a closed-loop or open-loop life cycle. From the closed-loop cycle perspective, a component will be reused or recycled for the same application (a tyre once again becomes a tyre), whereas materials and components enter another application in an open-loop perspective (a tyre may become artificial turf). Therefore, the PLC approach is considered as central for the development of more sustainable products, while the cascading methodology is central as the point at which the life cycle of a product ends and at least one new life begins at any of the reuse, recycling, or recovery levels (Kalverkamp et al., 2018). This definition implies a vision of a circular economy with almost no landfilling. However, since not all PLCs consider cascading use from the very beginning, the management of such cascading life cycles needs to be more adaptive. Pehlken et al. (2019) proposed a decision support tool (i.e., RAUPE), which is based on a platform approach, to support both the recycling and reuse of automotive parts, including electronic components (Pehlken et al., 2019). However, they said little about how such decision-making tools can be used to overcome the shortcomings that prevent the scalability of remanufacturing activities in mature and complex industries that produce highly polluting waste.

Accordingly, we have first identified the shortcomings involved in the effective implementation of remanufacturing activities within our case study, as obtained from the literature, and have then explored how the digital technologies implemented by a company help to overcome the local-scale shortcomings. Finally, we have provided a decision-making tool that overcomes the aforementioned large-scale shortcomings by exploiting platform logics to scale business models.

3. Methodology

We conducted an in-depth longitudinal study in the white goods sector to explore the shortcomings that prevent the scalability of remanufacturing activities in mature and complex industries that produce highly polluting waste and to find out how digital technologies can help to overcome them. As this methodology is considered appropriate to investigate a relevant phenomenon within its real context, we focused our analysis on the 2016–2022 period, as it coincided with the implementation of remanufacturing activities by Alpha – a leading European company in the distribution of spare parts for white goods (Yin, 1994).

Hereafter, we briefly describe the research setting (Section 3.1) and then move on to the data collection (Section 3.2) and the data analysis (Section 3.3).

3.1. *Case selection and description*

Digital technologies are gaining importance in the context of WEEE management as enablers of CE practices – in particular remanufacturing – as they introduce more efficiency to the circular processes and allow appropriate information to be shared (Milios, 2021). However, there are still significant challenges to achieving the potential triple-bottom-line benefits associated with implementing digital technologies within the context of large-scale remanufacturing in the WEEE industry. In this industry, the white goods sector accounts for over 40% of the total manufacturing and has recently been characterised by a profound shift in Extended Producer Responsibility policies that have changed the way manufacturers actively manage the end-of-life of their products by implementing upstream waste reduction strategies, such as reuse, repair, and remanufacturing (Dalhammar et al., 2021). In addition, the white goods industry also falls into the "right to repair" proposal, and new rules will apply in this industry. We conducted an in-depth longitudinal analysis, within the white goods sector, on the implementation of the remanufacturing activities the Alpha company has carried out since 2016 with the aim of remanufacturing and reselling damaged white goods otherwise destined for landfilling.

Alpha is an Italian family business that was founded in 1963 as a branch of a washing-machine manufacturer with the role of providing customers with technical support on repairs and the supply of spare parts. Today it is one of Europe's leading multi-brand distributors of spare parts and accessories for white goods, with 70 employees and a turnover of more than 21 million euros (a three-fold increase since 2008), and it deals with more than 50 brands.

We considered the Alpha company as a revelatory case study for the following reasons: (i) it represents a successful, profitable, and self-sustaining case of the implementation of the CE; (ii) its success and its remanufacturing activities are grounded on the exploitation of investments in digital data management technologies and the IT and physical infrastructure of the warehouse; (iii) although the results achieved with the remanufacturing activities are positive and quantifiable, from a triple-bottom-line perspective, digital technologies could improve their results, thus making such a company a 'revealing context' in which our phenomenon of interest could be 'transparently observed' (Yin, 1994, p.40).

3.2. *Data collection*

Relying on a combination of retrospective and real-time data collection (Pettigrew, 1990), we collected data over a period from 2016 to 2022 from multiple data collection streams, and multiple sources to both (i) gain a deeper understanding of the dynamics under examination by increasing the information base and diversifying data to reduce biases, and (ii) triangulate the data in order to strengthen the reliability and validity of our findings (Patton, 2014).

The sources of the secondary data were publicly available information and internal documents, and a total of 578 pages were examined.

The primary data collection was conducted in three phases between January 2019 and October 2022. During the first phase (between January and April 2019), one of the authors collected various data while spending several days at the Alpha company. Drawing on archive material collected on-site, we first produced an initial reconstruction of the historical and organisational context in which the Second Life implementation took place. We discussed our reconstruction on different occasions with three different informants, chosen because of their seniority and C-level role, to ensure the accuracy of our narrative and the validity of our reconstruction. In the second phase (from early May 2019 to September 2020), we focused our data collection efforts on the implementation of the new remanufacturing activities by conducting 12 interviews with nine members from nine different hierarchical levels, selected to ensure exposure to different perspectives, to compensate for personal biases and a lack of knowledge of individual informants, and to allow information provided by different informants to be cross-checked (Huber and Power, 1985). The interviews followed a semi-structured, open-ended protocol, lasted between 60 and 90 min, and were all recorded and transcribed. Because of the pandemic, the interviews conducted between March and September 2020 were conducted via video conference. A further 15 interviews were conducted in the third phase (2022), again following a semi-structured open-ended protocol, to refine and include additional questions suggested during the previous interviews. These interviews lasted between 60 and 90 min and were all recorded and transcribed. In total, we conducted 27 interviews with nine informants (Managing Director, Operations Manager, Registry Office Manager, Warehouse General Manager, Sales Manager, Human Resources Manager, Warehouse Director, Logistics Director) for an approximate total of about 49.5 h of recordings and 524 pages of transcription. Table 2 summarises the sources of primary and secondary data and their use in the analysis.

3.3. Data analysis

The data analysis was conducted according to the common prescriptions for longitudinal case studies (Langley, 1999; Yin, 1994). First, we reconstructed Alpha's history in detail, focusing on the implementation period of the Second Life remanufacturing project. This preliminary phase was followed by several rounds of data coding to look for patterns in the implementation of the Second Life project over time and in the interpretations of what our informants had proposed for the events they described (Stake, 1995).

Table 2
Data collection.

Data Source	Type of Data	Use in the Analysis
Semi-structured interviews	Obtained from 27 interviews: ● 11 interviews with the Managing Directors (Alpha + Second Life) ● 3 interviews with the Operations Manager ● 2 interviews with the Registry Office Manager ● 3 interviews with the Warehouse General Manager ● 2 interviews with the Sales Manager ● 2 interviews with the Human Resource Manager ● 2 interviews with the Warehouse Director ● 2 interviews with the Logistics Director	Used to trace the implementation dynamics of the remanufacturing activities in Alpha with the aim of mapping their processes and identifying their past and present shortcomings.
Secondary sources provided by informants	● Annual reports and company audits from 2012 to 2022. ● Technical documents on remanufactured white goods, spare parts, remanufacturing processes and on the warehouse and logistics management practices.	Used to fine-grain track the events, actions, and performances, as well as to triangulate the informants' statements and recollections.
Industry press	Archived documents on the implementation of remanufacturing activities in the white goods sector.	Used to track the external responses to remanufacturing challenges and opportunities.
Other publications	White papers and reports financed by Public Authorities.	Used to triangulate the informants' claims.

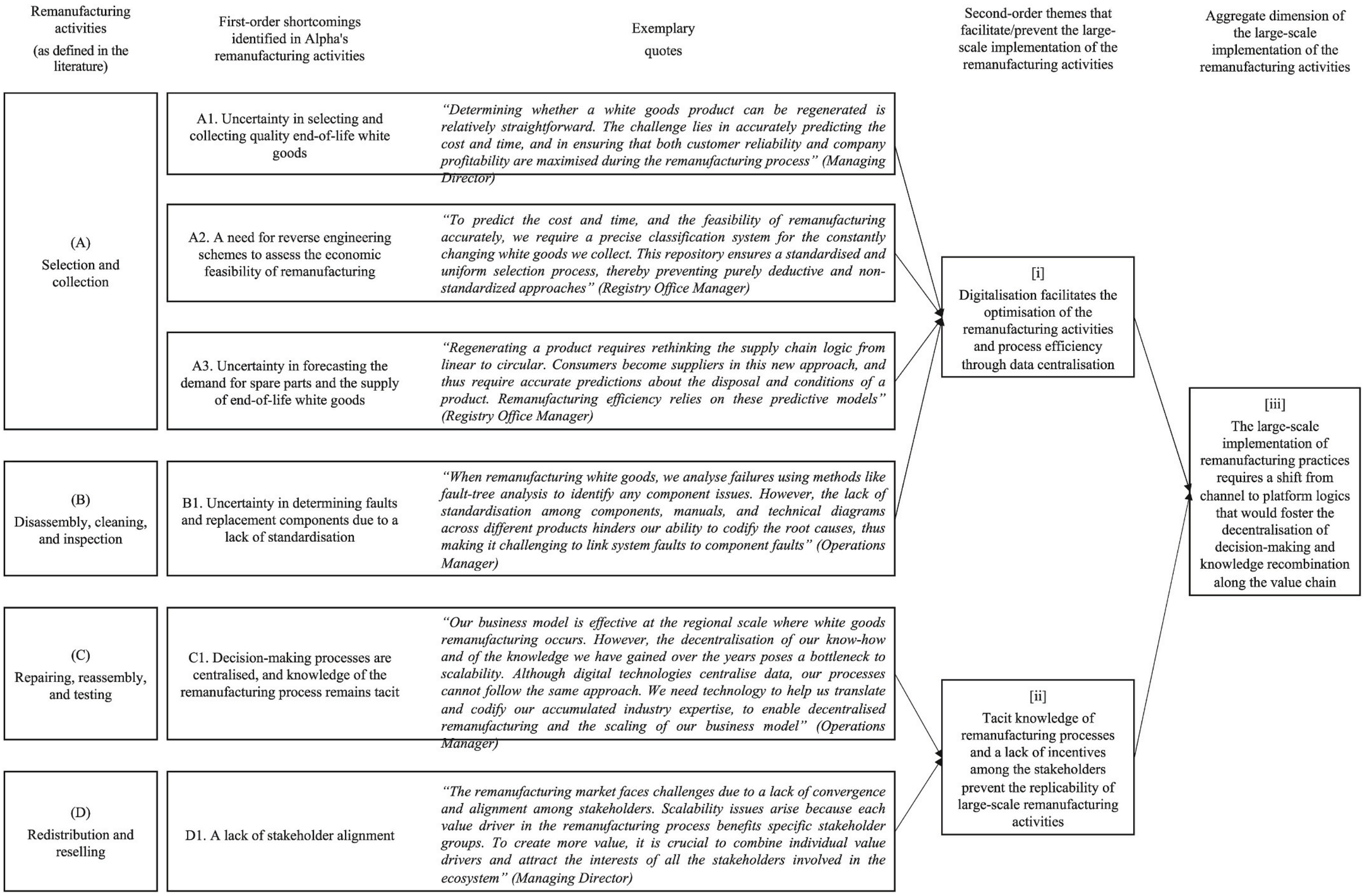
We coded for shortcomings in the Second Life remanufacturing project implementation practices and searched the data for any references to technological challenges associated with remanufacturing process activities. We coded our data in line with a more general understanding of the shortcomings associated with remanufacturing activities (Teixeira et al., 2022; X. V. Wang and Wang, 2019), not only for technological challenges but also for operational and strategic challenges associated with the implementation of remanufacturing activities. We coded these challenges, following previous research, in terms of remanufacturing activities related to the "selection and collection" of discarded products (e.g., Butzer et al., 2016; Gallo et al., 2012; Thürer et al., 2019; X. Wang et al., 2018), the "disassembly, cleaning and inspection" of components (e.g., Siew et al., 2020; Sundin and Bras, 2005; Yang et al., 2018), the "repair, reassembly and testing" of remanufactured products (e.g., Butzer et al., 2016; Siddiqi et al., 2019), and "redistribution and resale" on the market (e.g., Matsumoto et al., 2016; Ondemir and Gupta, 2014; Yang et al., 2018).

Two members of the research team proceeded in parallel. In order to ensure the internal consistency of the emerging coding structure (Miles and Huberman, 1994), we checked the reliability of our coding through the collective check-coding of previously coded texts. This process involved multiple iterations, as the emerging framework was constantly updated and revised on the basis of evidence collected in the subsequent interviews. We also routinely checked emerging interpretations with our contacts in Alfa (Strauss and Corbin, 1998, p.273). Triangulation with other sources and discussions with informants helped us to refine and strengthen the emerging interpretations throughout the process (Yin, 1994, p. 97). Internal and external archival sources – such as annual reports, analysts' reports and the business press – were particularly important to confirm ('triangulate') the informants' recollections of the challenges and efforts related to the implementation of remanufacturing activities.

The longitudinal nature of the study provided an opportunity to structure the data and examine the links between observations from different periods (Langley, 1999). Fig. 1 illustrates our emerging data structure of the shortcomings that prevent the scalability of remanufacturing activities in Alpha and illustrates the first-order concepts, second-order themes, and aggregate dimensions that serve as the foundation for our theorising (Gioia, Corley and Hamilton, 2013). In this way, Fig. 1 provides a structured illustration of the links between our raw data and the emerging theorisation that forms the cornerstone of our theoretical contribution. Following Locke (2001), we tested alternative conceptual frameworks until we had assembled the deficiencies into an overarching conceptual framework that fitted our evidence (Locke, 2001). We also used discussions on the emerging conceptual frameworks with colleagues and key informants as additional validity checks. Some powerful exemplary quotes are provided in Fig. 1, following the common prescriptions adopted for reporting qualitative data, to support our categorisation of the shortcomings that can impede the scalability of the remanufacturing activities that have emerged in this study. The following sections detail these themes and dimensions and begin to tie them together to create a coherent understanding of how pure technological adoption alone is not enough to make regeneration processes replicable at scale.

4. Findings

In 2016, Alpha introduced the "Second Life" project pertaining to the remanufacturing of white goods. Second Life consists of a closed-loop process that is used for the selection and remanufacturing of end-of-life white goods that are not severely damaged - or too obsolete – in order to resell them as fully functional products. Second Life is based on



Remanufacturing activities (as defined in the literature)	First-order shortcomings identified in Alpha's remanufacturing activities	Exemplary quotes	Second-order themes that facilitate/prevent the large-scale implementation of the remanufacturing activities	Aggregate dimension of the large-scale implementation of the remanufacturing activities
(A) Selection and collection	A1. Uncertainty in selecting and collecting quality end-of-life white goods	*"Determining whether a white goods product can be regenerated is relatively straightforward. The challenge lies in accurately predicting the cost and time, and in ensuring that both customer reliability and company profitability are maximised during the remanufacturing process" (Managing Director)*	[i] Digitalisation facilitates the optimisation of the remanufacturing activities and process efficiency through data centralisation	[iii] The large-scale implementation of remanufacturing practices requires a shift from channel to platform logics that would foster the decentralisation of decision-making and knowledge recombination along the value chain
	A2. A need for reverse engineering schemes to assess the economic feasibility of remanufacturing	*"To predict the cost and time, and the feasibility of remanufacturing accurately, we require a precise classification system for the constantly changing white goods we collect. This repository ensures a standardised and uniform selection process, thereby preventing purely deductive and non-standardized approaches" (Registry Office Manager)*		
	A3. Uncertainty in forecasting the demand for spare parts and the supply of end-of-life white goods	*"Regenerating a product requires rethinking the supply chain logic from linear to circular. Consumers become suppliers in this new approach, and thus require accurate predictions about the disposal and conditions of a product. Remanufacturing efficiency relies on these predictive models" (Registry Office Manager)*		
(B) Disassembly, cleaning, and inspection	B1. Uncertainty in determining faults and replacement components due to a lack of standardisation	*"When remanufacturing white goods, we analyse failures using methods like fault-tree analysis to identify any component issues. However, the lack of standardisation among components, manuals, and technical diagrams across different products hinders our ability to codify the root causes, thus making it challenging to link system faults to component faults" (Operations Manager)*		
(C) Repairing, reassembly, and testing	C1. Decision-making processes are centralised, and knowledge of the remanufacturing process remains tacit	*"Our business model is effective at the regional scale where white goods remanufacturing occurs. However, the decentralisation of our know-how and of the knowledge we have gained over the years poses a bottleneck to scalability. Although digital technologies centralise data, our processes cannot follow the same approach. We need technology to help us translate and codify our accumulated industry expertise, to enable decentralised remanufacturing and the scaling of our business model" (Operations Manager)*	[ii] Tacit knowledge of remanufacturing processes and a lack of incentives among the stakeholders prevent the replicability of large-scale remanufacturing activities	
(D) Redistribution and reselling	D1. A lack of stakeholder alignment	*"The remanufacturing market faces challenges due to a lack of convergence and alignment among stakeholders. Scalability issues arise because each value driver in the remanufacturing process benefits specific stakeholder groups. To create more value, it is crucial to combine individual value drivers and attract the interests of all the stakeholders involved in the ecosystem" (Managing Director)*		

Fig. 1. Data Structure of the shortcomings that prevent the scalability of Alpha's remanufacturing activities.

a series of complex and sequential activities that have been well defined in the literature (see Table 1 in section 2 of the Theoretical Background) and which include: (A) the selection and collection of white goods to be remanufactured on the basis of their quality and technical/technological obsolescence characteristics; (B) disassembly, cleaning, and inspection; (C) repairs, testing and cleaning; (D) redistribution and resale. As reported by Alpha's Managing Director:

> *"The Second Life project has opened up new opportunities for reverse logistics by enabling the transition to a circular economy and sustainable development. However, compared to traditional production systems, the shortcomings of remanufacturing activities are particularly complex and intrinsically linked to the remanufacturing processes themselves. Digital technologies have enabled us to optimise processes and create the efficiency necessary to overcome upstream shortcomings in remanufacturing* [i.e., "selection and collection" and "disassembly, cleaning, and inspection"]. *The downstream shortcomings* [i.e., "repairs, testing and cleaning" and "redistribution and resale"]*, on the other hand, are more complex because it is the technologies themselves that create new interdependencies. Overcoming these new shortcomings requires a paradigm shift at the supply chain level." (Alpha's Managing Director).*

As pointed out by the Managing Director, the adoption of digital technologies enabled Alpha to overcome the shortcomings that had, as a common denominator, the efficiency and optimisation of upstream remanufacturing activities (see A1, A2, A3, and B1 in Fig. 1). According to the Managing Director, the first shortcoming encountered in the effective implementation of remanufacturing activities was related to the selection and collection of quality the end-of-life white goods that could be remanufactured (see A1 in Fig. 1). At this stage, the level of uncertainty in the selection and collection of quality end-of-life white goods was extremely high, due to the lack of information on the condition of the product that had to be remanufactured. Furthermore, the ex-ante prediction and estimation of the extent of the repair costs - and thus the economic feasibility of the remanufacturing process - was a complex task, which was made even more complicated by the increasing number of product types on the market (see A2 in Fig. 1). Indeed, as corroborated by Alpha's Operations Manager:

> "Selecting a white goods product requires understanding, at an early stage, of the parts that can be repaired, anticipating the repair activities, and above all, being able to estimate the repair costs ex-ante. These tasks are far from simple, especially considering that similar appliances may often require completely different parts and repair activities, thus making the estimation of repair costs particularly complicated. Despite the many years of experience of our remanufacturing staff, making these kinds of decisions based on experience is not an option." (Alpha's Operations Manager).

The use of digital technologies has proved to be crucial in reducing uncertainty in the effective implementation of remanufacturing activities, especially in the selection and collection of white goods. As reported by Alpha's Operations Manager, it is crucial to understand, from the very first selection phase, what spare parts are needed, their stock availability, and above all, the economic feasibility of remanufacturing. Thus, Alpha invested in the computerisation of its warehouse and the digitisation of spare parts to minimise uncertainty in the selection and collection processes. This has enabled Alpha to build up a database over time that collects all the possible technical details of each spare part and the complete technical documentation of each product, which now has a total of over 2 million records. Thanks to this codification and digitalisation process, Alpha is now able to determine ex-ante the status and condition of the end-of-life products, the spare parts needed, their availability, and the remanufacturing costs and routines much more accurately than before. The digitalisation of spare parts has enabled Alpha to reduce the uncertainty in determining the remanufacturing cost, thus making the process of selecting cost-effective end-of-life products to be remanufactured from those not worth collecting more efficient.

The third shortcoming that Alpha's Registry Office Manager reported regarding the effective implementation of remanufacturing activities in the selection and collection phase concerns the difficulty of forecasting the demand for spare parts and the supply of end-of-life white goods (see A3 in Fig. 1). Remanufacturing requires a profound rethinking of the supply chain logics, from linear (OEM - distributor - consumer) to circular, in which the consumer becomes the supplier of the end-of-life products. However, predicting the quality and supply of these products and the spare parts needed to remanufacture them is a complex task that increases the uncertainty associated with remanufacturing activities. Hence, Alpha was faced with the need to become more data-driven in forecasting demand to reduce this uncertainty. As Alpha's Registry Office Manager reported:

> "Until 2005, the management of our spare parts was undertaken through an experience-based approach, whereby we adjusted orders to demand forecasts on the basis of past volumes. Starting in 2005, we decided to invest in a new demand planning software integrated with the warehouse management system. This allowed us to create a new relational database that was capable, on the one hand, of integrating high and diverse volumes of data from OEMs and end customers and, on the other hand, of providing the forecasting models required for remanufacturing and of highlighting key variables such as minimum reorder batches, spare part volumes by product type, and component failure statistics" (Alpha's Registry Office Manager).

The fourth shortcoming of the Second Life project that emerged from the case study concerns disassembly, cleaning, and inspection activities. At this stage, the level of uncertainty in determining faults and the components that have to be replaced is mainly due to the lack of standardisation of the components, manuals, and technical schemes across different product types (see B1 in Fig. 1). This significantly reduces the possibility of correlating technical information on spare parts with their relationship to faults, and it was a major obstacle for Alpha to optimise the remanufacturing processes and activities. Thus, Alpha invested in the digitalisation of manuals and technical diagrams of different types of white goods to optimise the use of logic-deductive methods, such as fault-tree analysis (FTA). This made it possible to standardise the root-cause analysis processes and to maximise both the remanufacturing process and the reliability of the remanufactured products.

In other words, the uncertainty in demand forecasting, the increasing complexity of information and the huge variety of spare parts that had to be processed prompted Alpha to enhance its IT infrastructure by using digital technologies, such as Cloud Computing and Big Data Analytics, and by introducing an increasing number of resources with Data Management and Data Analytics skills into the company. This process, based on the centralisation of data, coupled with the employees' experience and technical knowledge of the PLC, enabled Alpha to overcome the shortcomings in the "selection and collection" and in the "disassembly, cleaning, and inspection" activities (see [i] in the "Second-order themes that facilitate/prevent the large-scale implementation of remanufacturing activities" column in Fig. 1). This led to an increasingly efficient and standardised selection of end-of-life white goods, which were chosen on the basis of their quality and market value, but also, and above all, on the basis of the economic feasibility of the remanufacturing process and the reliability of the remanufactured products.

Although this data centralisation approach may lead to an increasing decentralisation of the remanufacturing activities close to the customer, the case study revealed that two unexpected shortcomings, originating from the data centralisation process itself, now limit the scalability of the project at the regional level in the downstream stages of the remanufacturing process (see C1 and D1 in Fig. 1). In order to extend the impact of the triple-bottom line benefits enabled by the Second Life project, in terms of environmental protection, economic viability, and social equity at a national and international level, it is necessary for the good practices and knowledge accumulated by Alpha over the years to be somehow 'codified' and made scalable (see C1 in Fig. 1), while taking into account the interests of the different stakeholders along the supply chain (see D1 in Fig. 1). Indeed, although the centralisation of data has optimised and streamlined the upstream remanufacturing activities, it has also created more organisational complexity by introducing new interdependencies between the knowledge underlying the remanufacturing activities. This additional complexity makes the transfer and recombination of knowledge quite challenging and, together with the lack of incentives and strategic alignment of the stakeholders' interests along the supply chain, prevents the replicability of remanufacturing activities at a large scale (see [ii] in the "Second-order themes that facilitate/prevent the large-scale implementation of remanufacturing activities" column in Fig. 1). As the Managing Director reported:

> "Overcoming process bottlenecks that result from the implementation of large-scale remanufacturing activities involves new technological challenges and requires new organisational approaches. The adoption of digital technologies has enabled us to be efficient, innovate our business model, and differentiate ourselves. Now, in order to scale our business and bring remanufacturing to scale, we need to adapt a locally developed business model to a large-scale environment that takes into account changes at the ecosystem level and no longer at the supply chain level, and which is also able to align different stakeholders' interests by moving from a channel logic to a platform logic." (Alpha's Managing Director).

As pointed out by Alpha's Managing Director, to make the Second Life project scalable at a large scale, it will be necessary to decentralise the decision-making processes by favouring a knowledge recombination of the product, its life cycle, maintenance, repairs and spare parts along the supply chain (see [iii] in the "Aggregate dimension of the large-scale implementation of remanufacturing activities" column in Fig. 1). However, this decentralisation mechanism requires a shift from traditional linear channel logics (those with which the remanufacturers operate today - see Fig. 2a) to platform logics based on circular and organic interdependencies between the different stakeholders of the value-chain (i.e., OEMs, retailers, end-customers and WEEE collectors - see Fig. 2b). This would allow Alpha to activate a new relational system among its supply chain actors in order to replicate the decision-making processes related to the decentralisation of the repairing, reassembly, and testing activities (C1 in Fig. 1) and to align the stakeholders' interests in redistribution and reselling activities (D1 in Fig. 1). In other words, activating a platform-based model that would allow Alpha to share data and knowledge with selected users (subject to a set of constraints and rules, depending on whether they are B2C or B2B users) by exploiting the logic of crowdsourcing and the typical value co-creation mechanisms of digital platforms and by generating a set of positive and circular externalities at the ecosystem level (see Fig. 2a and b).

As corroborated by the Managing Director, a platform-based model, such as the one depicted in Fig. 2b, would allow the stakeholders involved in the white goods supply chain to achieve several win-win advantages. First, it would enable remanufacturers, such as Alpha, to source spare parts from OEMs, as they would receive comprehensive and standardised technical data. At the same time, the OEMs would not only feed the market with spare parts, but also benefit from a decentralised network of remanufacturers and data on the remanufacturing process, thereby allowing them to optimise their product development and inventory strategies at a zero marginal cost and without incurring cannibalisation risks. Indeed, although the profit margins of remanufactured products are usually comparable with those of new products, whether

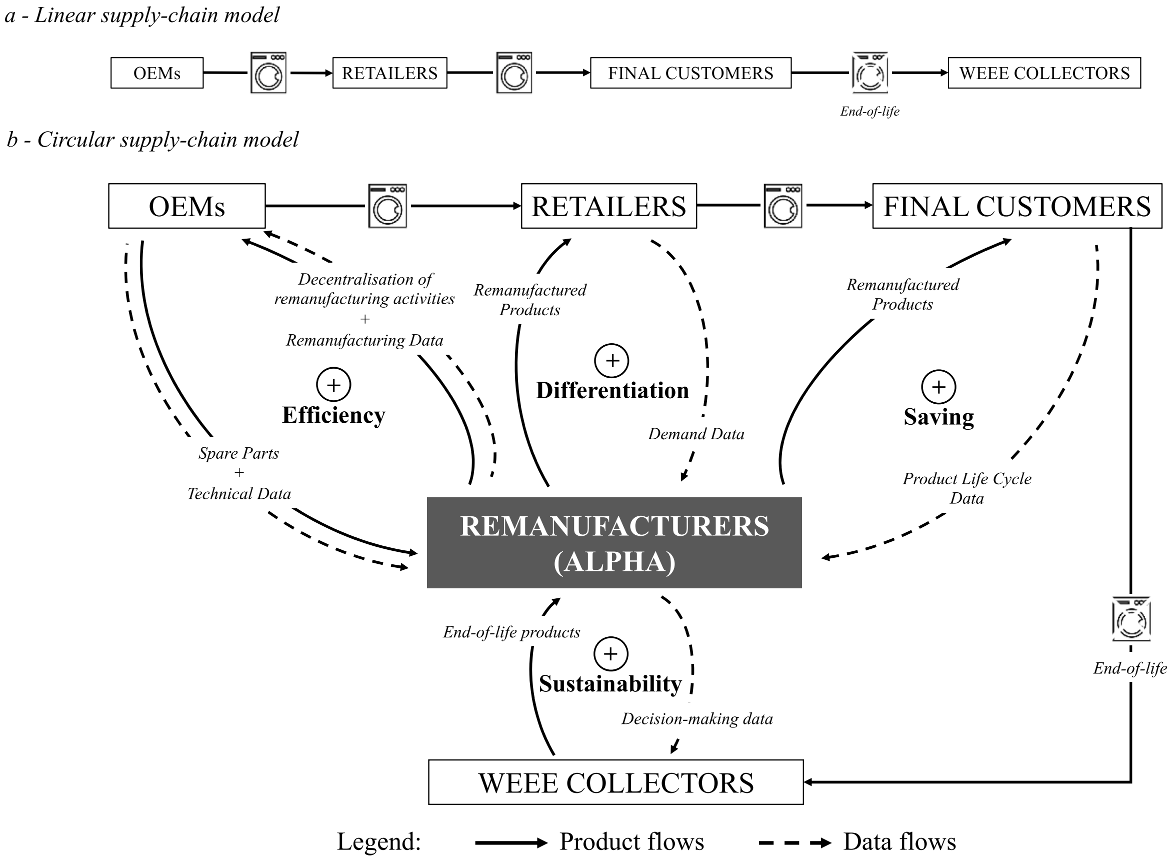


Fig. 2. The new relational system between stakeholders in the white goods supply chain proposed in this study.

profits are cannibalised by remanufacturing depends on the customers' perceived value. Furthermore, independent remanufacturing differs from authorised (independent) remanufacturing, where OEMs authorise third parties to remanufacture. This indicates that OEMs can also profit from remanufacturing and that cannibalisation is not a deal-breaker per se. Second, it would enable retailers to differentiate their offers by reselling not only new products supplied by OEMs but also products remanufactured by a certified remanufacturer network. Furthermore, remanufacturers would benefit from new data to predict the demand for spare parts and the supply of end-of-life white goods. Third, it would allow the final customers to save money by purchasing remanufactured products directly from the remanufacturers (thus avoiding double marginalisation on the resale of remanufactured products) and would provide remanufacturers with a unique set of data on the PLC to improve decision-making and failure prediction models over time. Finally, the platform model would allow WEEE collectors to differentiate between products to be disposed of and cost-effective end-of-life products to be remanufactured, thus generating sustainability benefits and self-sustaining the remanufacturing process in a circular manner.

In order to make remanufacturing projects, such as Second Life, scalable and to overcome the shortcomings that currently limit their replicability at a large scale, in the following section, we apply a decision-making tool that had been designed for the automotive industry, which is based on a circular logic and on a digital platform logic, to the white goods sector, thereby showing how digital technologies can help overcome the shortcomings of remanufacturing in this sector and facilitate its scalability.

5. Discussion

The evidence gathered in this study has shown how digital technologies have enabled Alpha to develop a successful business model that can be used for the effective implementation of remanufacturing activities in industries that produce highly polluting waste. Although digital technologies have enabled Alpha to centralise data and knowledge on remanufacturing processes on the basis of a cascade-used methodology (Kalverkamp et al., 2017), traditional channel logics have limited the scalability of the business model at the local level (Eisape, 2022).

On the one hand, Alpha's use of technology has streamlined and optimised the upstream remanufacturing activities (i.e., "selection and collection" and "disassembly, cleaning, and inspection") by improving the connections between objects, individuals, and processes through data centralisation. This approach is aligned with previous studies on the challenges of remanufacturing and on the potential of digital technologies and data centralisation to overcome the related shortcomings. For example, Ma et al. (2019) showed how cloud computing - by enabling centralised processing, flexible data storage and scalable service capabilities - supports the self-awareness, self-organisation, self-adaptation and self-confrontation capabilities needed to make remanufacturing activities efficient. Similarly, Wang et al. (2020) showed how Big Data Analytics – used as a tool to extract meaningful value from data in remanufacturing systems - facilitates the acquisition of valuable information regarding customers, products, and their usage (Ehret and Wirtz, 2017; Kireev et al., 2018), attracts target consumers (Bressanelli et al., 2018), predicts and maps the market demand (Neto and Dutordoir, 2020) and increases the sales and return rates (Xiang and Xu, 2019; Xu et al., 2019).

On the other hand, the results show that although the centralisation of data has allowed the upstream remanufacturing activities to be made efficient and become optimised, it does not guarantee the replicability of the large-scale, decision-making processes of the downstream activities (i.e., "repairs, testing and cleaning" and "redistribution and resale); in fact, the opposite occurs. The centralisation of data creates more organisational complexity as it introduces new interdependencies between the knowledge that underlies the remanufacturing activities. This additional complexity makes the transfer and recombination of knowledge somewhat challenging and, together with the lack of incentives and strategic alignment of the stakeholders' interests along the supply chain, prevents the replicability of remanufacturing activities at a large scale. Taken together, our evidence shows that to fully reap the technological efficiency benefits generated at a local scale and to replicate them at a large scale, it is necessary to shift from traditional linear channel logics to platform logics based on circular and organic interdependencies between the different actors in the value chain.

In the following, a decision-making tool that had been designed for the automotive industry, which has a circular logic and is based on the logic of the digital platform, is applied to the white goods sector. Fig. 3 shows the architecture of the decision-making tool proposed in this study to make remanufacturing projects, such as Second Life, scalable and to overcome the shortcomings that currently limit their replicability at a large scale.

The decision-making tool is based on a digital platform logic and on data mining methods applied to a centralised database, and it can provide not only information on spare parts but also relevant answers to support large-scale remanufacturing decisions, with emphasis on independent actors. This tool is not only in line with our findings but also contributes to the European Circular Economy Action Plan by supporting the "right to repair" rule. Platforms are part of the whole "right to repair" concept. In the past, the priority was that of replacing rather than of repairing products when they became defective, and consumers were not encouraged to repair their goods after the legal guarantee had expired. The aim of the "right to repair" is to simplify and make the repairing of goods more affordable for consumers rather than forcing them to resort to replacement. This not only increases the demand for repair services, but also encourages producers and sellers to adopt more sustainable business models. Platform concepts are dealt with together with the stakeholders along the supply chain, and a "European Repair Information Form" has been planned for consumers to assist them in their choices related to repairing and remanufacturing products.

The decision-making tool proposed in this study is built upon the RAUPE solution, which was applied as a prototype to the automotive sector in 2018 (Pehlken et al., 2019) to support a decision-making process on the reuse of a spare part. The modular design approach of the RAUPE platform enables easy extension of its scope to address the shortcomings highlighted in this study. This can be achieved by incorporating additional contextual information for the stakeholders involved, particularly remanufacturers and potential suppliers of used products (such as consumers and recyclers). Such an enhancement aims to facilitate informed decision-making for large-scale remanufacturing. The RAUPE platform originally considered four stakeholder groups: consumers, government auditors, distributors, and recyclers. The main functionalities of RAUPE are its ability to integrate user-generated data and to provide product-specific information on critical materials, and it includes a criticality indicator based on the EU criticality assessment. The material content of the products is used to show the recyclability potential and its potential to contribute to urban mining (which means a saving of primary raw materials). The more so-called "critical materials" are involved, the greater the impact. The platform, when applied to the Alpha case, focuses on consumers, retailers, remanufacturers, and on WEEE collectors. At present, the proposed platform solution does not consider OEMs, as, to the best of the authors' knowledge, the remanufacturing activities in the white goods sector are mostly driven and performed by third parties (Alpha in our case), who also hold the product data needed to conduct the remanufacturing activities (Veleva and Bodkin, 2018). This situation is typical of many industrial contexts in which OEMs share only a part of the product information, thereby forcing third parties to build up their own knowledge base (for example, the automotive sector).

Should OEMs be involved in the future, they could leverage on such a platform, for example, by establishing revenue streams through authorised remanufacturing or other licenced services where spare parts are provided and information on the PLC is part of the "revenue" stream. This does not require OEM-owned remanufacturing assets or activities. Thus, OEMs would not only be able to participate in but also enhance the

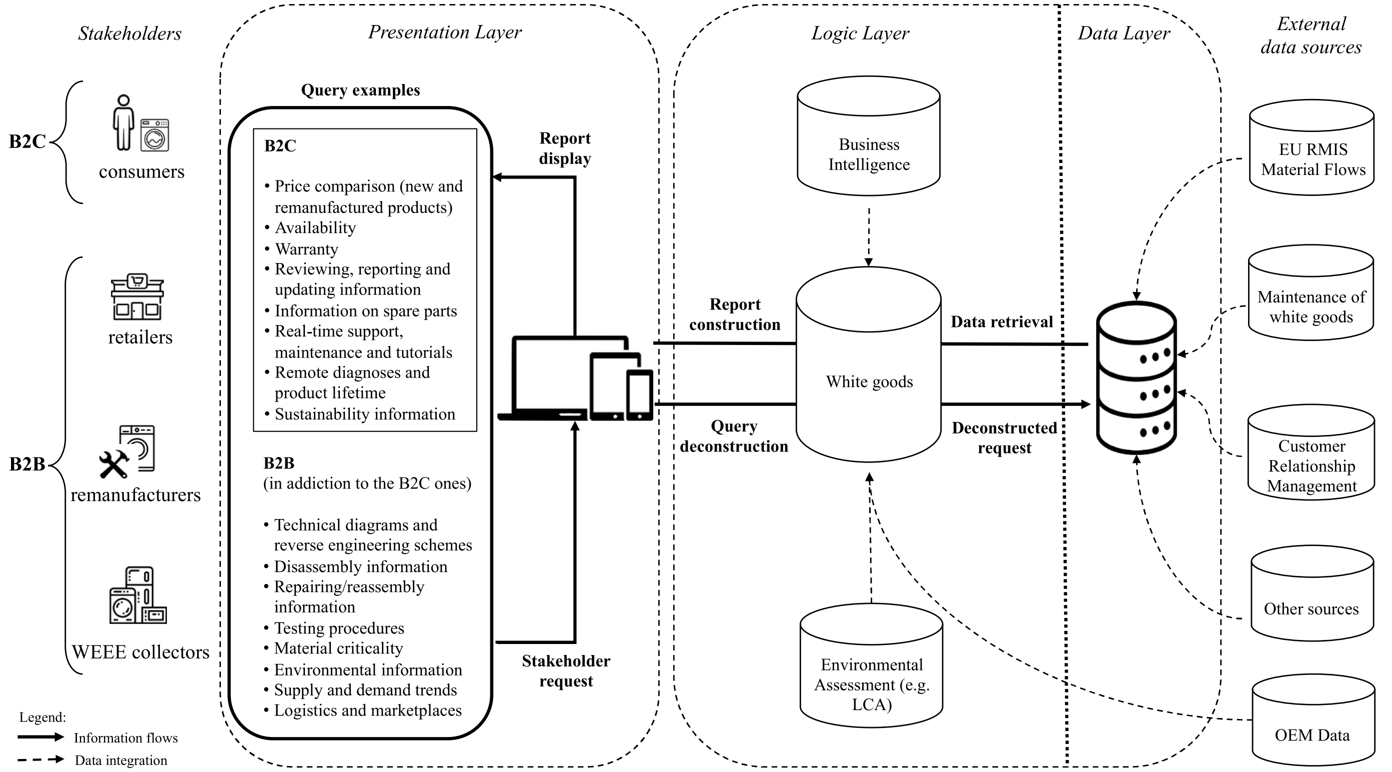


Fig. 3. Platform architecture of the decision-making tool proposed in this study.

potential of remanufacturing by reducing the impact of the identified shortcomings, especially regarding the need to reverse engineer and the uncertainties in determining faults (A2 and B1 in Fig. 1). Although the current developments, such as the “right-to-repair” and some practical examples/applications (e.g., Catena X in the automotive industry) encourage the participation of OEMs in remanufacturing activities, their participation could also lead to the strategic alignment of the other platform partners being challenged. Such a scenario emphasises the need for the platform (owner) to provide rules of the game that would limit the risk of strategic misalignment (related to low strategic alignment, D1 in Fig. 1).

The identified stakeholders can determine the requirements for the different levels of the platform. At the presentation layer (top layer), the platform provides a responsive website with information on the specific stakeholders’ interests (see “Query examples” in the Presentation Layer in Fig. 3). In the case of white goods, B2C users can request information on, for example, price comparisons between new and remanufactured products, availability, warranty, reviews, spare parts, real-time support, tutorials, remote diagnosis, product lifetimes, and sustainability information. B2B users, in addition to the information accessible to B2C users, have access to other information, such as technical diagrams and reverse engineering diagrams, disassembly information, repairing/reassembly information, test procedures, material criticalities, environmental information, supply and demand trends, and information on logistics and marketplaces. Therefore, the website could provide different stakeholder groups with relevant information and, eventually, a recommendation on whether a product (or component) should be reused, repaired or recycled, as well as information on how to conduct the respective actions (e.g., what parts to dismantle and how). Both remanufacturers and WEEE collectors could benefit from sustainability information, especially if the legislation provides benefits for these third-party activities that could increase the reuse and recycling of the products. This level benefits from the ability to integrate user-generated data. Such information improves the quality of data and thus supports decision-making because it offers the opportunity to close the interrupted data flow between development, production, and after-sales. Finally, if there is a unique identifier per product, engineers, or even consumers, can provide product-specific information, for example, on parts replaced during the life cycle and product life.

The logical layer (second layer) handles user queries and data entry via the website. Thanks to the separation from the presentation layer, new interfaces can be developed with relatively little effort (e.g., via Application Programming Interfaces - APIs), thus meeting the specific needs of different stakeholders. For instance, in the case of washing machines, remanufacturers, retailers, and recyclers might want to assess the environmental impact of a product throughout its life cycle and its potential reuses by linking a Life Cycle Assessment (LCA) interface to the platform to improve decision-making at the ecosystem level. It should be noted that an LCA interface only makes sense if data from the manufacturer is available, otherwise, it mainly acts as a black box.

The core of the platform, at the data layer, is the back-end database. The RAUPE solution is based on a constantly updated local database, which is populated through web services or external databases (such as technical maintenance manuals for white goods, the Raw Material Information System – RMIS, and Customer Relationship Management systems – CRM). Since Alpha manages its own database with information on its products and spare parts, the proposed platform could easily be implemented by leveraging on Alpha’s existing technology infrastructure, while still ensuring the same degree of control over the data. However, in order to maximise the ecosystem-wide benefits, in terms of scalability of the business model, we propose a hybrid approach that involves moving the database to the cloud to improve connectivity with different stakeholders and speeding up services using its content, such as Business Intelligence (i.e., a technology-driven process used for analysing data and delivering actionable information to help make informed business decisions).

The advantage of a decision support tool, based on such a platform, is connected to its ability to incorporate and link different data sources from different parties. In this way, remanufacturers can use their product knowledge to increase the reach of their business and thus scale their activities. The constant use and updating of product data enable the translation, codification, and sharing of information that would otherwise remain the tacit knowledge of individual experts. The combination of user-generated data and data mining allows the platform to “learn” and improve its decision support and, in particular, to address the shortcomings related to the centralisation of the decision-making processes, thereby ultimately reducing the dependency on tacit knowledge (see C1 and (ii) in Fig. 1). The platform supports the search for and recombination of knowledge between consumers, retailers, remanufacturers, WEEE collectors, and other potential third parties, without compromising the knowledge base of the platform owner (Alpha in this case), thus solving the shortcomings related to the need to make tacit knowledge explicit for third parties and aligning the interests of different stakeholders along the value chain (see C1 and D1 and (ii) in Fig. 1). These search and recombination mechanisms are a key element of the platform, as they can allow regenerators to create value from regenerated products without compromising the appropriateness regimes that result from the exploitation of the database. This is particularly important as far as the scaling of remanufacturing activities is concerned. Independent remanufacturers, in a similar way to (OEM-) authorised remanufacturers, could establish new business models via the platform, for example, by providing valuable disassembly or remanufacturing information for certain remanufacturers outside their market (region); however, this would require a careful evaluation to ensure that their proprietary knowledge was protected.

Thus, the limitations of previous approaches, all of which required the remanufacturer’s experts to make ad hoc and on-site decisions, could be reduced or even eliminated. In addition, the platform offers remanufacturers and dealers an opportunity to reach more potential customers, e.g., with special buy-back offers for used products in combination with the sales of remanufactured products. This would generate a win-win solution at the ecosystem level, in terms of the circular economy: on the one hand, remanufacturers and retailers could expand their market and increase their sales; on the other hand, consumers would be incentivised to remanufacture white goods rather than dispose of them and buy new ones. In this way, the platform would increase stakeholder alignment and support the decentralisation of decision-making processes by facilitating the recombination of knowledge about the product, its life cycle, maintenance, repairs and spare parts along the supply chain (see [iii] in Fig. 1).

6. Conclusion

This study explores the shortcomings that can prevent the scalability of remanufacturing activities in mature and complex industries that produce highly polluting waste. Our results show that digital technologies play a key role in overcoming the high levels of complexity that currently characterise – and, at the same time, limit - the successful large-scale implementation of remanufacturing activities.

Table 3 provides a comprehensive summary of the findings of this study, and shows the remanufacturing activities as defined in the literature (Column 1), the shortcomings identified in the scalability of Alpha’s remanufacturing activities (Column 2), the shortcomings that the adoption of digital technologies can help to resolve and those that it creates when implemented in remanufacturing activities (Column 3), and, finally, the shortcomings that could be resolved not simply “by adopting” but “by adapting” digital technologies to the new ecosystem (Column 4). The results show that the shortcomings of the upstream activities of remanufacturing can be overcome, at a local scale, by adopting digital technologies, such as Cloud Computing and Data Analytics, to centralise data (see Column 3, what we call “Making the dots”). However, the mere adoption of these technologies does not guarantee

Table 3
"Making the dots" at a local scale vs. "Connecting the dots" at a large scale.

Remanufacturing activities (as defined in the literature)		Shortcomings identified in the scalability of Alpha's remanufacturing activities	"Making the dots" at a local scale: using digital technologies to do things differently	*"Connecting the dots" at a large scale: adapting digital technologies to the new ecosystem*
Upstream remanufacturing activities	(A) Selection and collection	A1. Uncertainty in selecting and collecting quality end-of-life white goods A2. A need for reverse engineering schemes to assess the economic feasibility of remanufacturing A3. Uncertainty in forecasting the demand for spare parts and the supply of the end-of-life quality white goods	Digitalisation facilitates the optimisation of remanufacturing activities and process efficiency through data centralisation: ● The digitalisation of spare parts and technical documentation for each product ● The computerisation of the warehouse ● The creation of databases in which all the possible technical details of products and spare parts are collected ● Investments in demand planning software integrated with the warehouse management system ● The development of relational databases to integrate large and diverse volumes of data and to highlight such key variables as the minimum reorder batches, spare part volumes by product type, and component failure statistics	The large-scale implementation of remanufacturing practices requires a shift from channel to platform logics that fosters the decentralisation of decision-making and knowledge recombination along the value chain: ● The inclusion of third-party knowledge and an exchange of product data with different stakeholders, including OEMs, re-manufacturers, WEEE collectors, consumers and other potential third parties ● Research and a recombination of knowledge among the stakeholders, without compromising the knowledge base of the platform owner ● The indication of the critical material content to show the recyclability potential and its potential to contribute to urban mining ● Improving demand forecasts by using data from consumer demands ● Extending existing solutions by connecting external data sources (databases and user-generated data) via a cloud infrastructure ● Translating, coding, and exploiting the know-how through which data should be interpreted ● Broader and more available knowledge to improve ad-hoc and decentralised decision-making (such as reuse or recycling), without the need to maintain expertise and tacit knowledge on site ● The creation of a shared knowledge base from multiple sources to reduce the knowledge gap with OEMs ● Sharing the digital product passport (in the near future) ● Experimentation of 'trustworthy' tools for the supply chain stakeholders, e.g., a distributed ledger.
	(B) Disassembly, cleaning, and inspection	B1. Uncertainty in determining faults and replacement components due to a lack of standardisation		
Downstream remanufacturing activities	(C) Repairing, reassembly, and testing	C1. Decision-making processes are centralised, and knowledge of the remanufacturing process remains tacit	Digitalisation creates higher organisational complexity and new interdependencies between the knowledge that underlies the remanufacturing activities ● Knowledge remains tacit, thus preventing the replicability of large-scale remanufacturing activities ● A lack of incentives among stakeholders prevents the replicability of large-scale remanufacturing activities	
	(D) Redistribution and reselling	D1. A lack of stakeholder alignment		

the replicability of decision-making processes in downstream activities; in fact, the opposite is true. The centralisation of data creates more organisational complexity by introducing new interdependencies between the knowledge that underlies the remanufacturing activities. This additional complexity makes the transfer and recombination of knowledge somewhat challenging and, together with the lack of incentives and strategic alignment of the stakeholders' interests along the supply chain, prevents the replicability of remanufacturing activities at a large scale. The Alpha case shows that, to fully reap the technological efficiency benefits generated at a local scale and replicate them at a large scale, it is necessary to shift from traditional linear channel logics to platform logics based on circular and organic interdependencies between the different actors in the value chain (see Column 4, what we call "Connecting the dots"). The decision-making tool proposed in this study acknowledges this required shift and provides the technological basis to scale remanufacturing activities in mature and complex industries that produce highly polluting waste, such as the white goods sector.

From a theoretical perspective, the study contributes to the circular economy and remanufacturing literature in two ways. First, starting from the shortcomings in the implementation of remanufacturing activities indicated in the literature, the study provides empirical evidence of how digital technologies can help companies overcome such shortcomings. Second, the study unveils two new idiosyncratic tensions triggered by digitalisation and how they limit the replicability of large-scale remanufacturing activities. From a practical perspective, the study proposes a decision-making tool that can be used to overcome these shortcomings by exploiting platform logics to scale remanufacturing activities in mature and complex industries that produce highly polluting waste, such as the white goods sector. Such a tool provides an environment that helps transfer the tacit knowledge of remanufacturing engineers and experts to new actors connected to the platform. In this way, decision-making processes no longer remain anchored in the physical world or limited by geographical distances, and they can be replicated at a large scale. Furthermore, the decision-making tool was designed with a modular logic, enabling scalability through the addition of new services. These services include recommendations regarding the advantages and disadvantages of remanufacturing specific white goods, tutorials on disassembly and remanufacturing using Augmented and Virtual Reality for non-expert users, as well as additive manufacturing services for the on-demand production of specific spare parts. In addition, the proposed approach is aligned with the EU's circular economy strategy and supports the right to repair. Combining the platform with a digital product passport could further enhance resource efficiency. However, the degree of information sharing necessary for OEMs with somewhat distant value chain partners is still rare in practice, and strong regulation is still missing. Nevertheless, even without OEM participation, the platform can function as a lever to scale (independent) remanufacturing activities.

Despite the empirical value of our contribution, the study suffers from some limitations related to the adopted methodological approach. Although the longitudinal approach with which we conducted the case study allowed us to attain a deep understanding of the phenomenon under investigation, the specificities of the context limit the external validity and generalisability of the results we obtained from a single case study. These limitations open the way for further research. First, we propose empirically evaluating the impact of the platform in the white goods sector to see whether our findings can be confirmed, extended or even revised. Second, it would be appropriate to assess the applicability of the platform proposed in this study in other adjacent sectors that share similar boundary conditions to the white goods sector, such as sectors where products have several components but some of them break more frequently than others; sectors where repairing costs more than buying a new product; sectors where the logistics of spare parts are complex and economies of scale and scope are important. Although our evidence shows that the proposed platform logics can help overcome the shortcomings and bottlenecks that limit the replicability of remanufacturing activities at a large scale, we believe that such logics entail additional technological challenges and organisational complexities that need to be investigated.

CRediT authorship contribution statement

Claudia Franzè: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Danilo Pesce:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Matthias Kalverkamp:** Methodology, Writing – original draft, Writing – review & editing. **Alexandra Pehlken:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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