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RESEARCH ARTICLE

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Scaling up a circular business model for remanufacturing: A case study of a sustainable value creation strategy for the white goods industry

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Abstract

Because of the ever-increasing pressure on producers to adopt environmentally responsible industrial practices, remanufacturing has emerged as a key strategy to address the challenges of resource conservation and waste reduction. In this paper, we address a conspicuous research gap regarding innovative and large-scale circular solutions in the form of *remanufacturing systems*. We investigate how the private sector can build widespread remanufacturing networks to handle waste from the appliance industry. Starting from a successful case study of a leading Italian distributor of spare parts, our analysis expands their existing business model and inductively develops an original framework for regional remanufacturing. Our resulting model encompasses a centralised hub specialised in high-tech data management and supply-chain logistics, coupled with two tiers of remanufacturing labs and repairers, diffusing triple-bottom-line benefits throughout the local territory. We discuss the generalisability of such a centralised/decentralised model and propose avenues for the policy support of systemic circular innovations.

KEYWORDS

circular business model, remanufacturing, strategy, sustainability, value creation, WEEE industry

1 | INTRODUCTION

Among the various circular economy (CE) strategies that involve the industrial restoration of used products, remanufacturing is considered a compelling and innovative approach (Goodall et al., 2014). Such a strategy is environmentally preferable to other value recovery options, because it conserves the 'embodied energy' and the materials used during the primary manufacturing processes (Linder & Williander, 2017). Despite remanufacturing having gained increased attention, due to its potential to deliver triple-bottom-line benefits across environmental, economic and social dimensions (D'Adamo & Rosa, 2016), to date, we have observed a lack of large-scale practical implementations. These implementations are particularly relevant for the management of waste from highly polluting sectors, such as Waste from Electrical and Electronic Equipment (WEEE), one of the most rapidly expanding waste streams worldwide, with over 50 million tonnes generated in 2020, a total that is expected to rise to 70 million by 2030. As such, the end-of-life management of these products represents not only a major environmental and health policy concern, due to the complex and hazardous composition of electronic

Abbreviations: CE, circular economy; CEAP, circular economy action plan; CO2eq, CO_2 equivalent; EEE, Electrical and Electronic Equipment; GDP, Gross Domestic Product; GDP, Gross Domestic Product; GWP, global warming potential; ICT, Information and Communications Technology; kg, kilograms; LCA, Life Cycle Assessment; M€, million euros; NGO, Non-Governmental Organisation; OEMs, original equipment manufacturers; VAT, value-added tax; WEEE, Waste from Electrical and Electronic Equipment; WM, washing machine.

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components (Aminoff & Sundqvist-Andberg, 2021; Bressanelli, Saccani, Pigosso, & Perona, 2020; Talens Peiró et al., 2022), but also an opportunity to promote sustainable economic development throughout a territory (Geissdoerfer et al., 2020).

In such a context, innovative solutions and alternative circular business models are needed in parallel with classic waste management strategies that ensure the proper collection, transportation, treatment and disposal of waste (Bahers & Kim, 2018). However, even though the potential benefits of WEEE remanufacturing are well known (Ghisellini et al., 2016; Sundin & Lee, 2012), its remanufacturing industry still remains small in scale and narrow in scope. As a result, its positive impacts are confined to a limited territorial coverage (Bressanelli et al., 2019b; Goodall et al., 2014; Kara, 2010). Moreover, most of the studies on CE remanufacturing solutions for this sector have focused on micro-level evidence on a single product or company while the meso level—eco-industrial parks and industrial symbiosis projects - have seldom been contemplated and virtually no analysis has been conducted on macro-level systems—at a city, regional, national or international level, involving ecosystems of multiple stakeholders (Ghisellini et al., 2016; Liu et al., 2019; Scarpellini et al., 2019).

Some recent studies have called for further research on the operational and strategic mechanisms needed to scale a remanufacturing business model to a broader geographical area, considering technological and logistic constraints, market structures, local demands and the surrounding policies, regulations and legislation (Franzè et al., 2023; Pesce et al., 2023). An integrated perspective is fundamental to bridge the gap in the economic approaches that consider remanufactured product costs (Jiang & Zheng, 2022; Jochen, 2015; Neto et al., 2016) with managerial perspectives that model how to strategically organise resources, know-how, skills and the flows of products and information into a large-scale remanufacturing structure (Tonelli & Cristoni, 2019; Xia et al., 2022). Moreover, previous studies have highlighted a need to broaden the research scope of circular business models towards an ecosystem perspective that includes multiple stakeholders (consumers, local retailers, public service operators, etc.) and not only a company-centric viewpoint (Alblooshi et al., 2022; Hunka et al., 2020; Kanda et al., 2021; Tapaninaho & Heikkinen, 2022). This shift is also aligned with the growing interest in sustainability and the participation of the consumers, local governments and public/private companies that operate in the sector and provide environmental services.

Therefore, this study adopts an integrated perspective to offer new evidence-based insights into the scaling up of a circular business model for remanufacturing. We address the following research question:

How should an integrated remanufacturing system be implemented at a macro/regional level to spread triple-bottom-line benefits?

In order to address this research question, we conducted an empirical analysis on an in-depth case study (Yin, 2017) to provide the basis necessary to inductively develop a model of a large-scale system for the sustainable remanufacturing of large appliances, one of the most problematic categories of WEEE, in terms of lifecycle extension and remanufacturing (Linder & Williander, 2017). Compared to small electronic devices, such as phones or computers, large home appliances such as dishwashers, fridges and washing machines have limited second-hand markets due to the high repair costs, the lack of affordable spare parts and the expensive logistics involved in transporting these heavy products (Parker et al., 2015; Van Loon et al., 2020). Consequently, many large appliances are discarded even for minor malfunctions, thereby worsening the problem of the ever-growing WEEE and squandering valuable materials. Thus, this sector can be considered a 'revealing context' (Yin, 2017) to observe the phenomenon of interest and to model remanufacturing at a systemic scale that could be generalised to other sectors and territories.

We base the model of our remanufacturing system on a real circular business model already implemented by a company operating at the municipal level in the North-West of Italy, which provides the baseline that informs our analysis. This company already has a small-scale remanufacturing activity that profitably recovers discarded appliances of any brand, remanufactures them with workers from disadvantaged backgrounds, and sells them in low-income areas. However, their business model has a limited geographical scope, as it is concentrated within a single company and only covers the urban areas around the main city, and thus suffers from several bottlenecks that hinder the expansion of the current system. The main motivation for adopting this case study as a starting point is that it would allow us to harness the best practices from this company and to identify its key challenges to develop an empirically-grounded proposal for a large-scale remanufacturing system that could be applicable at the regional and/or cross-regional level. We develop a theoretical framework for this inductively scaled-up remanufacturing network as a two-tier hub-and-spoke model that combines numerous small, decentralised repair and remanufacturing business units with a central hub to obtain highly digitised supply chain logistics and data management. In our model, large and heavy products have to travel the shortest possible distance, while knowledge and spare parts are transferred over longer distances. Moreover, from the case study, we inductively derive the main triple-bottom-line value creation strategies, using a theory-building process that illustrates our resulting propositions through the use of a concrete example.

We contribute to the CE literature by grounding our theoretical model of a large-scale remanufacturing network on a practical existing business reality, and we maintain the strengths of the case study in our model while proposing new scalable solutions to address the bottlenecks faced by smaller-scale operations. We also characterise the benefits of this remanufacturing system to derive policy and managerial implications. We argue that leveraging on innovative digital technology can help optimise the organisation of the remanufacturing value chain, thereby creating a brand new 'second life' market for high-quality, affordable appliances. Indeed, according to our estimates, and as a back-of-the-envelope calculation, the scaling up the remanufacturing of washing machines in the Piedmont region alone could save 5–8 million kg of CO2eq. annually.

The remainder of the paper is structured as follows. Section 2 discusses the literature and theoretical background of the study. Section 3 presents our methodological approach. Section 4 describes the results, which are then discussed in Section 5. Section 6 concludes with policy implications and future research avenues.

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2 | THEORETICAL BACKGROUND—CIRCULAR ECONOMY, REMANUFACTURING AND TERRITORIAL COVERAGE

In this section, we contextualise our analysis of remanufacturing within the existing literature on CE theories at different geographic scales. Section 2.1 summarises the CE models that involve remanufacturing at different territorial levels (micro, meso and macro). Section 2.2 zooms into the literature by studying the advantages and challenges of remanufacturing models which, although integral with CE practices, predominantly focus on micro-level evidence. Finally, Section 2.3 considers different potential network structures that are suitable for designing a well-functioning remanufacturing system.

2.1 | Circular economy models for remanufacturing at different scales

In recent years, there has been a burgeoning amount of literature on new CE business models applied to the electrical and electronic industry, and which approach different 'R' strategies (reduce, recycle, redesign, etc.); however, the evidence on remanufacturing is still limited. Researchers have explored various aspects of CE at multiple levels and in numerous contexts, ranging from its theoretical underpinnings to its practical applications. The focus of these broad investigations has spanned from micro-level analyses of individual products and firms to macro-level assessments of regional, national and global systems. The economic geography dimension of circular practices is known to be a central factor for those supply chains built around goods that are not easily transported over long distances, such as large and heavy appliances, whose spare parts entail complex logistics, as for most white goods.

Most of the studies on remanufacturing in the current literature on CE models have focused on the micro level. These studies often analyse the optimal pricing, quantity, viability, feasibility and economic considerations of remanufacturing (Li et al., 2017; Reimann et al., 2019). Other studies have separately examined the actors involved in remanufacturing, such as the original equipment manufacturers (OEMs) and third parties, and their challenges (Berssaneti et al., 2019; Vogt Duberg et al., 2023). Several studies, from the broader circular business model perspective, have examined specific case studies at the company level (Geissdoerfer et al., 2023; Hofmann & zu Knyphausen-Aufseß, 2022), but this literature has not integrated firm-level insights with more complex circular systems.

The current research still lacks in-depth investigations into remanufacturing systems, technologies and stakeholders' interactions at the meso and macro levels. The conducted meso-level studies on industrial symbiosis have established connections between companies and stakeholders to amplify CE endeavours, with a certain relevance on remanufacturing practices for white goods (cf., Kobayashi et al., 2020; Marconi et al., 2018). At the macro level, heterogeneous studies, spanning different geographic dimensions, have provided a general context for remanufacturing and similar practices, although none have specifically concentrated on remanufacturing (Sigüenza et al., 2021; Talens Peiró et al., 2022). Thus, larger remanufacturing systems have not yet been modelled, especially those concerning home appliances. For a detailed summary of the relevant literature at these levels, see Table A1.

In Table 1, we summarise the most recent themes explored by this literature in the past few years, which have been used to inform our analysis and fill the main gaps, classified according to their theoretical or practical relevance.[1]

From a theoretical perspective, these CE models have only recently started to focus on systemic interactions and enabling technologies. However, the evidence on CE systems for the management of WEEE is still limited, and it primarily focuses on recycling and reduction strategies and overlooks the potential economic and social benefits for the local communities (Barreiro-Gen & Lozano, 2020; Bressanelli, Saccani, Pigosso, & Perona, 2020). Moreover, the systemic benefits of CE in WEEE industries have not been investigated or quantified, as the macro implementation of CE models remains largely unexplored (Scarpellini et al., 2019). From a practical viewpoint, among all the different CE activities, the literature has emphasised how the existing remanufacturing industry is limited in size and scope (Linder & Williander, 2017; Liu et al., 2019), thereby hindering the diffusion of its potential triple-bottom-line benefits across a wider regional ecosystem (Kanda et al., 2021; Talens Peiró et al., 2022; Vogt Duberg et al., 2023). A key challenge that has been identified is that large appliances are difficult to both transport and disassemble and that they require complex logistics and advanced know-how to be remanufactured (Li et al., 2013; Scarpellini et al., 2019; Wang & Wang, 2019b).

In the next section, we provide a more detailed framework that distinguishes between the remanufacturing system and the process, and we analyse the relevant literature on its implementation challenges and triple-bottom-line benefits.

2.2 | Challenges and opportunities for remanufacturing at a large scale

Remanufacturing is a value recovery and product life extension strategy that applies a set of industrial activities to maintain products at the highest possible economic value, with reduced environmental impacts, for the longest time possible (Butzer et al., 2016). A *remanufacturing process* restores discarded products to a like-new condition through inspection, cleaning, repair, reassembly and testing, whereas a whole *remanufacturing system* organises the entire supply chain from waste collection all the way to the final sales on the second-hand market (Vogt Duberg et al., 2020). Figure 1 illustrates a complete remanufacturing system, with the remanufacturing process at its centre.

A linear supply chain starts with the extracting, processing and transporting of raw materials, which OEMs subsequently employ in

[1] For a review of the previous evidence on CE models at different geographic scales up to 2015, see Ghisellini et al. (2016).

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TABLE 1 Research gaps highlighted in the recent circular economy literature, focusing on WEEE and large appliances.

Gaps in the existing circular economy (CE) models of remanufacturing and for WEEE		References
Theoretical, as highlighted from literature reviews and conceptual studies	The CE models in the WEEE industry mainly address reduce and recycle strategies and pay limited attention to reuse and remanufacture practices.	(Barreiro-Gen & Lozano, 2020; Bressanelli, Saccani, Pigosso, & Perona, 2020)
	The CE models in the WEEE industry focus on the economic benefits, for the supply chain, of 'recycling' and on the financial savings for users from 'reducing' approaches. Instead, the social impacts and how the reuse, remanufacture and recycle strategy can generate economic benefits for local societies have received very little attention.	
	The benefits of the CE have not yet been investigated or quantified in a systemic manner. Whether CE in the EEE industry can (or cannot) contribute to sustainability with a win-win-win strategy remains an open question.	
	To date, studies that have addressed the implementation of CE models from a macro perspective are still rare.	(Scarpellini et al., 2019)
Practical, as highlighted from empirical studies	The current remanufacturing industry is small in scale and narrow in scope.	(Linder & Williander, 2017; Liu et al., 2019)
	There is a lack of a regional sustainable remanufacturing system: Even though studies of systemic WEEE management exist, the approaches in specific regions or beyond the urban scale have not been well developed.	(Bahers & Kim, 2018; Kanda et al., 2021)
	The reparability and circularity of (large) electronics and appliances are challenging because the design of such products generally makes them unsuitable for disassembly, and the industry lacks data, know-how and enabling technologies for circularity and lifetime extensions.	(Wang & Wang, 2019b)
	There is a lack of data on the potential triple-bottom-line benefits and spillovers of remanufacturing at the local level.	(Talens Peiró et al., 2022; Vogt Duberg et al., 2023)
	The transport logistics of a large appliance are complex: a large-scale approach is not an appropriate approach for this kind of WEEE, and local short-distance solutions would be better. • The Basel convention on the control of transboundary movements of hazardous wastes and their disposal forbids the international movement of WEEE, without the prior consent of all the involved states. • The EU encourages the limited circulation of waste across European borders (principle of territoriality)	(Li et al., 2013; Scarpellini et al., 2019)

the manufacturing of new products. These products are sold to consumers through wholesalers and retailers. After a period of use, the consumers dispose of the product, usually in a landfill. This linear process is illustrated in the top part of Figure 1. However, in order to achieve a more circular structure, further activities are needed to 'close the loop' and reintegrate some end-of-life products back into the economy. To this end, a remanufacturing system transforms the linear supply chain into a circular one, in which spare parts and components are procured, the remanufacturing process itself is implemented and, ultimately, the remanufactured goods are resold (Farahani et al., 2019; Vogt Duberg et al., 2020). Discarded products that are suitable for remanufacturing are collected from WEEE centres (or directly from customers) and transported to the remanufacturing sites through a take-back system (illustrated on the right of Figure 1). The collected WEEE can be used directly for remanufacturing, if the products are in good condition; alternatively, they may be disassembled to salvage parts for repairs. Only after exploring these options are the remaining materials disposed of in landfills (as shown at the bottom of Figure 1). The remanufacturing process is the central industrial activity implemented by remanufacturers within this system (see the centre of Figure 1); however, all the other actors and stakeholders who participate in the overall system are necessary to coordinate the rest of the supply chain. The overall management of the system adopted to 'close the loop' presents both challenges and triple-bottom-line benefits for the local economy. The challenges of effectively scaling remanufacturing activities at a macro/regional level are shown in Figure 2.

Remanufacturing activities above all have to face significant challenges in *production planning and control*, due to the intrinsic uncertainties in the quantities, quality and timing of the discarded products. More precisely, the unpredictable conditions of end-of-life products, and of their demand and supply (Butzer et al., 2016), result in irregular and fluctuating batch sizes that cannot be managed homogeneously (Gallo et al., 2012). These complexities also contribute to inventory management issues, a key problem for companies since the efficient and affordable sourcing of spare parts is crucial for a timely and financially viable process. *Selecting* discarded products involves considering the quality, market value, and the likelihood of successfully remanufacturing the product to avoid excessive replacement costs. The state of products that have been returned and their components typically remains unidentified until disassembly and inspection (X. Wang et al., 2018). A subsequent *collection* from logistics centres relies on a

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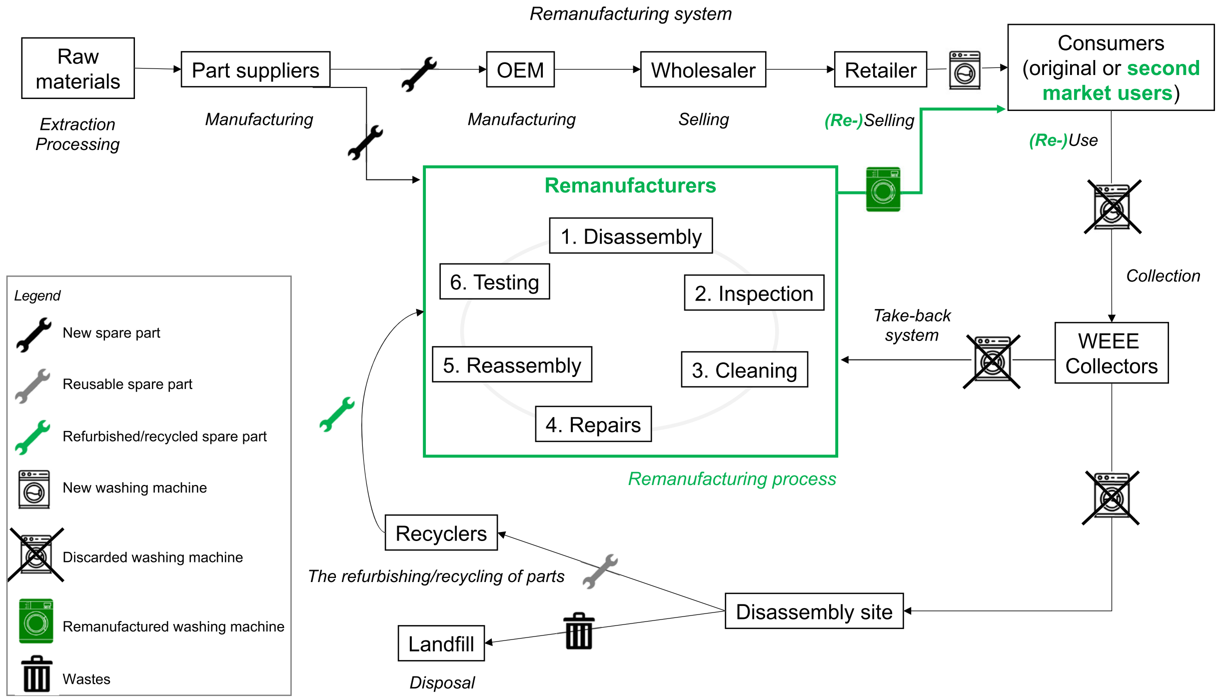

FIGURE 1 Remanufacturing system and process from a macro-level supply-chain perspective. *Source*: Authors' own elaboration from Farahani et al. (2019).

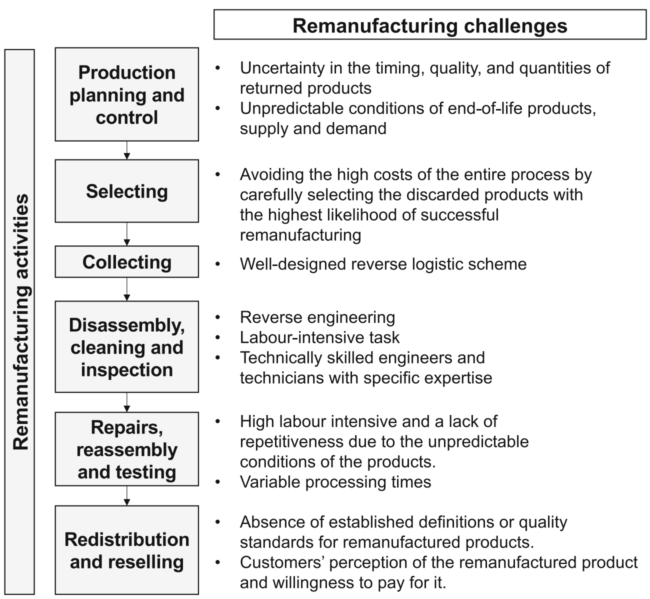

FIGURE 2 The challenges of effectively scaling remanufacturing activities at a macro/regional level.

well-designed reverse logistic scheme (i.e., a take-bask system) and the distance between WEEE disposal centres and the remanufacturing plant is a key cost factor (Islam & Huda, 2018; Thürer et al., 2019).

In the *disassembling* phase of a discarded product, third-party companies frequently resort to reverse engineering, due to the absence of standardised data on a product's characteristics. Consequently, disassembly, cleaning and inspection become labour-intensive tasks that require skilled technicians with specific expertise (Siew et al., 2020; Yang et al., 2018). Moreover, the *repair*, *reassembly* and *testing* activities are also labour-intensive and lack the possibility of repetitiveness due to unpredictable product conditions, and this leads to fluctuating processing timeframes (Siddiqi et al., 2019). Finally, the remanufactured product is *redistributed* and *resold* to customers as brand-new, complete with a warranty and after-sales services, albeit at a reduced price. Quality assurance relies largely on the condition of the received end-of-life product, and this can present challenges due to the absence of established remanufactured product standards across different sectors (de Vicente Bittar, 2018; Ondemir & Gupta, 2014). Clients may hesitate in recognising the value of a remanufactured product or be reluctant to pay a comparable price to that of a new product (Yang et al., 2018). When remanufacturing is carried out by independent entities rather than OEMs, there is generally no incentive for cooperation between remanufacturers and standard producers, which, therefore, results in a lack of information exchange between them (Matsumoto et al., 2016).

Altogether, these challenges could inhibit the large-scale implementation of remanufacturing (Linder & Williander, 2017). Therefore, our paper is aimed at addressing these issues by leveraging on digital technologies to build a regional model that is based on an existing municipal-level case study. Implementing remanufacturing solutions that take advantage of the latest digital technologies has the potential to overcome the limitations that hinder the scalability and standardisation of the remanufacturing activities discussed above (Franzè et al., 2023). The existing literature recognises that, theoretically, the triple-bottom-line benefits of a remanufacturing system on the local economy can be sizeable. However, this literature has rarely

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considered remanufacturing systems or the large-scale implementations of remanufacturing. We summarise the most relevant benefits of such practices in Table 2.

At the same time, in recent years, there has also been a growing body of literature that has critically evaluated the assumptions and limitations of CE paradigms (Lehmann et al., 2023). These studies have highlighted various trade-offs that need to be considered carefully in the pursuit of circularity. For example, scholarly research has pointed out the high energy and resource intensity of remanufacturing and recycling processes (Huether et al., 2022; van Allen et al., 2022). Indeed, it has underscored the possibility that circular products, despite their improved environmental performance from their extended lifespan and use of recycled materials, may consume more energy than new products that feature superior energy efficiency ratings (Dahm, 2022; Strand, 2022; Vahle et al., 2022). Moreover, circular economy solutions can also sometimes result in the production of lower-quality goods, which could mean running the risk of contamination and the presence of hazardous residual substances, and they can involve inherent uncertainties in the utilisation of secondary resources, thereby complicating the safe and efficient use of the recovered materials (Corvellec et al., 2022).

Furthermore, implementing circular practices may require additional logistics and transportation, which entail further energy requirements and, depending on the transport modes, additional pollution and emissions (Llorach-Massana et al., 2015). Finally, circular business models may fall short of addressing the underlying causes of the persistent resource problems that necessitate radical innovations or behavioural changes, particularly in the context of globally dispersed value-creation networks (Hofmann, 2019). Overall, this literature emphasises the need for a careful assessment of the net benefits

TABLE 2 The triple-bottom-line benefits of remanufacturing as taken from the literature.

Triple-bottom-line outcomes	References
Environmental benefits. Remanufacturing is preferable to new product manufacturing because: • It preserves the embedded value (energy, materials and labour) resulting from the efforts made when manufacturing new parts e.g., material extraction, material manufacturing, part manufacturing and product manufacturing. • It contributes to the savings of energy and of scarce raw materials, resources and carbon, and reduces the need of extracting virgin resources from the environment, which is achieved by using secondary resources taken from the recycling of WEEE, thus avoiding the impacts of new material production along with its related energy-intensive mining and CO_2 emissions (upstream). • It solves the problem of the waste of valuable scraps and reduces the amount of generated waste, especially through life extension or recovery options (downstream).	(Farahani et al., 2019; Goodall et al., 2014; Linder & Williander, 2017; Low & Ng, 2018; Sitcharangsie et al., 2019; Vogt Duberg et al., 2020; Zlamparet et al., 2017)
Economic benefits • It reduces production costs as a result of using secondary materials or recovered components, with costs that have been estimated to be around 40%–60% lower for remanufactured electric appliances. • It protects the industry against volatile material prices and supply disruptions. • It increases the awareness of the potential impacts of future material criticality. • It serves a market segment that is currently not well developed (second-hand appliances). • It generates further revenues from the selling of recycled materials or recovered components and from additional services such as maintenance and repair. • It enhances innovation and further optimises electronic manufacturing thanks to rich information about the performance of such products.	
Social benefits • It creates employment opportunities at the local level as remanufacturing tends to be a labour-intensive task, due to the need for certain hand-made processes, such as disassembly. • It enables increased access to products or services for people with low incomes thanks to the lower price of reused or remanufactured products. • It reduces the informal or improper discarding of WEEE, which can lead to the toxic contamination of soil, water and air, and can affect human health.	

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of any circular model in which the potential negative impacts of remanufacturing are also considered.

2.3 | Circular economy networks: spatial coverage of the remanufacturing system

Implementing a regional remanufacturing system requires a strategic approach that encompasses logistics, data and knowledge management, and the adoption of innovative digital solutions to achieve a balance between efficiency, cost-effectiveness and responsiveness in the movement of goods and the provision of services within the circular supply chain (Tonelli & Cristoni, 2019; Xia et al., 2022). As discussed earlier on, large appliances pose the most significant challenges concerning transportation, because of their size and weight and their disassembly due to the high number of components. Moreover, remanufacturing requires specialised competencies and investments that not all companies are willing to provide or are capable of developing. Finally, large market players like OEMs, which can access more advanced technological solutions for upscaling purposes, are often reticent to participate in circular activities that create second-hand goods which could be in competition with their new products. In this context, designing a well-functioning remanufacturing system requires considering the different possible network structures that link the key stakeholders operating in the system and defining how the goods, services, knowledge and technology are organised and flow. We have drawn on insights from the logistics and trade literature, as well as from the data network topology literature, to assess some of the possible options (Wang & Wang, 2011, 2019a; Xu et al., 2021). Many different types of link space structures exist that could characterise the system shown in Figure 1, such as a star network, a ring network, a path network, a tree network, and mixed networks. However, the application of such networks to CE models has only been scantly developed, and even less so in the context of remanufacturing (Deng et al., 2023).

Such systems have different properties, depending on how the actors at the nodes of the network exchange information and send goods to the other nodes. For instance, a fully decentralised system (mesh-type network) ensures that all the actors are fully interconnected in a system that is rather complex but also highly resilient to disruptions. Conversely, a bus network is the closest to a linear supply chain model, whereby each node only 'communicates' (sends parts, sells goods, etc.) to the next one, all the way to the landfill. A circular network instead allows unidirectional or bi-directional exchanges to take place between nodes organised in a closed loop. Star models or hub-and-spoke models allow one main stakeholder to centralise some activities in the heart of the network and then exchange physical and intangible products with distributed, 'peripheric' stakeholders throughout the territory. Although the circular network may resonate more directly with CE concepts, we have focused on star or hub-and-spoke topologies as valid solutions for remanufacturing due to the need to encourage the coverage of an extensive territory while centralising innovative high-tech solutions to exploit scale and scope economies.

3 | RESEARCH METHODOLOGY: A CASE STUDY FROM THE WHITE GOODS INDUSTRY IN ITALY

We conduct an in-depth case study of an Italian company that operates in the white goods sector to investigate how an integrated remanufacturing system should be implemented to spread triple-bottom-line benefits at a macro/regional level. This type of case study allows researchers to analyse a contemporary phenomenon in depth and its actual context, to examine the developments over time in the phenomenon of interest and to explore the factors that contribute to these changes (Yin, 2017). Given the paucity of systemic remanufacturing solutions for large electrical products, our study starts from a well-functioning circular business model that was developed by a single company to build a large-scale integrated system of remanufacturing in a 'revealing context' in which the phenomena of interest could be 'transparently observed' (Yin, 2017).

The considered case serves two purposes for our paper: first, the analysis of its current strengths highlights key elements that should be present in a larger regional remanufacturing system, while the bottlenecks faced by the company when growing its remanufacturing activities represent the main challenge that a wider integrated system should address. Second, from the case study we inductively derive the main triple-bottom-line value creation strategies to estimate some of the tangible local benefits with a concrete example from this Italian region and for theory building, and to illustrate our resulting propositions.

In this section, we present details on how we analyse the information from the case study inductively and, drawing upon the most appropriate network framework, we build our theoretical model of a large-scale remanufacturing system. Subsequently, we combine the data from the case study with some regional data on the local territory where the company is located to characterise the benefits of scaling up in the context of North-West Italy. Section 3.1 presents the empirical research setting, Section 3.2 deals with the data collection and Section 3.3 indicates the data analysis methodologies.

3.1 | Empirical research setting

3.1.1 | Case description: 'Ri-generation', a remanufacturing business at the municipal level

In order to build our large-scale remanufacturing model, we start with an in-depth case study of an existing remanufacturing business, which currently operates at a small scale, through a mixture of manual and automated processes, and combines advanced technological solutions and supply chain management to make remanufacturing viable, at least at the municipal level. This remanufacturing business is embedded in a large Italian company, Astelav Srl, a family business established in the 1960s as an offshoot of a washing machine manufacturer, which is specialised in spare parts and components for the industry. In 2016, Astelav established a subsidiary company,

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Ri-generation, which is dedicated to remanufacturing large home appliances. Both Astelav and Ri-generation are located within the same plant just outside the regional capital, Turin. Initially launched as an experiment to build expertise on the repair needs of customers, the Ri-generation project has gradually become a fully functional localised system for remanufacturing and reselling discarded appliances. The remanufacturing activities currently occur in a Ri-generation laboratory (called 'Ri-Lab'), a 100 m^2 space located within the Astelav premises, where technicians are responsible for remanufacturing household appliances. The processes handled in the Lab are more mechanised and systematic than those of a simple repair shop, but do not entail a high-tech capital infrastructure or the conduction of large-scale operations by the central company.

In recent years, Astelav has developed its physical and digital technological resources, and thus its supply-chain management efficiency, with investments that have reinforced its market leadership and supported the innovative and closed-loop business model of Ri-generation. In 2022, Astelav was one of the leading multi-brand European distributors of spare parts and accessories for large home appliances (washing machines, dishwashers, refrigerators and other appliances), with 70 employees, a turnover of more than 20 million Euros (a total that had tripled in just 10 years) and a portfolio of products that cover around 50 different brands. The company's exceptional logistics, that is, their ability to ensure the delivery of any spare part in 12–24 h,[2] positions it as a promising candidate for a pivotal role in a large-scale remanufacturing system.

Astelav, with its successful trajectory, has propelled the Ri-generation remanufacturing project, and this has resulted in a growing demand for remanufactured products. Currently, the main bottleneck lies in the productive capacity of the facilities, as all of the remanufactured products are quickly sold out at a 50% lower price than new ones. Elasticity of demand is crucial to consider upscaling, with Ri-Generation currently processing about 4000 products annually, and an expansion throughout the territory would increase the quantity of discarded appliances that are suitable for remanufacturing.

Despite this, the company's managers remain optimistic about the potential demand for second-hand appliances, as a result of their affordability, quality (which is ensured by a two-year warranty and a seven-year average lifespan) and the increasing sensitivity of its customers towards environmental impacts. Changing lifestyle trends, such as frequent the relocation of workers and students for short periods, create another market segment that could benefit from remanufactured appliances.

Remanufacturing activities are highly labour-intensive, as they require superior know-how about a product and the lifecycle of its components (Tolio et al., 2017). For this purpose, Astelav recruited unemployed workers who had been laid off from some major appliance companies operating in the same area and leveraged on their skills for Ri-generation. Additionally, young individuals from challenging social backgrounds were hired as interns through a local NGO[3] programme. These individuals learned to use existing databases and developed specific skills to identify the 7–10 components subject the most to 'wear and tear' in advance, thus making remanufacturing efficient on average after just 1 h of diagnosis plus 2–3 h of direct labour to remanufacture and test a washing machine or refrigerator.

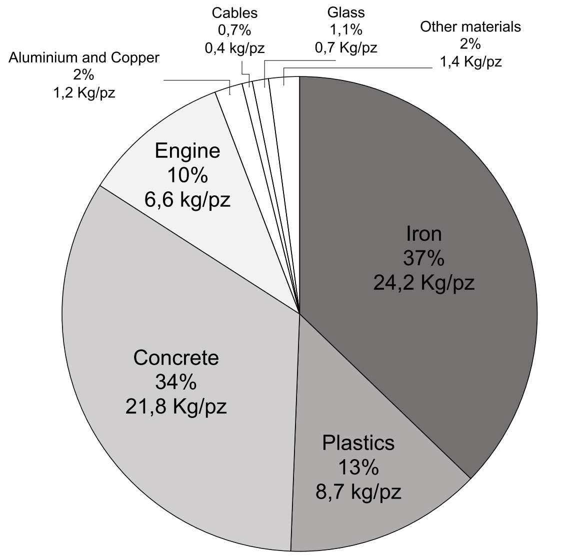

FIGURE 3 Average material composition of a 65-kg washing machine. *Source*: RAEE, 2012.

3.1.2 | The market for appliances and washing machines

The second contextual element of our analysis pertains to the appliance market in the territory under study. Since our aim was to inductively build a scaled-up remanufacturing system, it is necessary to acknowledge the characteristics of the examined context, since they can affect the generality of the developed model. The Italian market for large domestic appliances represents a typical European reality of a wealthy nation that is undergoing a sustained growth in national production and consumer demand (APPLiA, 2023). We chose the washing machine, a heavy product with a high potential for remanufacturing, as our main home appliance of the analysis. Washing machines are durable goods that are usually characterised by a medium-long lifespan and a significant consumption of resources (detergents, electricity and water) during their use. However, this lifespan varies according to the frequency of use, the quality of the machine and how well it is maintained (Ellen MacArthur Foundation, 2012). Even though washing machines are generally conceived as standardised products, they exhibit variations in their composition and weight, and contain more than 20 different materials (see Figure 3, RAEE, 2012). Italians have the highest household ownership rate of washing machines in Europe. The qualities sought in

[2]In 2021, Astelav implemented a new automatic vertical warehouse, which increased the picking efficiency from 40 Stock Keeping Units/minute to almost 200. Moreover, it uses data analytics to select spare parts stored in the warehouse and is able to handle about 40,000 pieces of the 2 million potential components.

[3]Youth Missionary Service Association, URL: https://en.sermig.org.

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these appliances concern performance, energy efficiency and durability, with some recent trends emerging in connectivity and sustainability (APPLiA, 2023; Bressanelli et al., 2019a). Thus, a remanufacturing model that intends to serve this market at a large scale should provide products that are not only more sustainable, thanks to the circular recovery of the products, but also guarantee high quality.

In many cases, it is not financially feasible to remanufacture such home appliances as washing machines on the existing market. Some components can be replaced easily and cheaply, while in other cases, substituting damaged parts requires significant amounts of time and money. The remanufacturing of washing machines mostly involves the replacement of the circuit board and the rubber door seal (Enel, 2017). The collection of such heavy products is typically not cost-efficient for original equipment manufacturers. Consequently, remanufacturing operations are generally undertaken by independent remanufacturers with specialised capabilities who are situated in close proximity to the suppliers of used products (Jin et al., 2022).

3.1.3 | Opportunities for a regional remanufacturing system in the Piedmont region

We then consider the economic, demographic and environmental characteristics of Piedmont, our baseline territory of analysis in North-West Italy, where Astelav and Ri-generation are both based. This region was chosen for multiple reasons. First, it is among the most competitive Italian regions in the manufacturing industry, which means that the production and logistic systems are well-developed and efficient from the technological infrastructure and skilled workforce perspectives (Vrontis et al., 2018). Moreover, its strategic position, close to central and western Europe, favours proximity to the suppliers and markets, thereby reducing transportation costs and time and facilitating supply chain efficiency. Additionally, Piedmont forms part of a key industrial triangle of northern Italy (Turin-Genoa-Milan) and has a GDP per capita of more than 30,000€/year (Istat, 2023). Therefore, the local population has a good purchasing power for new appliances and their regular replacement. Finally, it is the fourth most populous region in Italy, with a population of over 4 million inhabitants, with 80% living in a few large cities and their surrounding areas and the rest widely distributed across the region (Istat, 2023). Piedmont comprises eight provinces, with Turin, its capital, being the largest city (the fourth Italian Functional Urban Area in terms of population) and its leading industrial centre (Figure 4). Thus, it is possible to approximate the number of washing machines in use from the population density, since the penetration rate of this appliance is close to 100% (APPLiA, 2023). See Table B1 for further details on the demographic profile of the region under study.

Italian legislation regulates all the actions and protocols required to enhance, prevent and diminish the adverse effects that stem from the manufacturing of Electrical and Electronic Equipment and the associated waste (Legislative Decree 49/2014 no. 49). Appendix C summarises the relevant Italian regulations. Consistently with the type of waste and its hazardousness, household WEEE is collected according to five different groupings to facilitate its treatment: R—Refrigeration appliances (refrigerators, freezers, etc.); R2—Large household appliances (dishwashers, washing machines, etc.); and R3–R5, which covers all the other electronic categories. When an electronic or electric piece of equipment is discarded, it becomes WEEE and must be treated accordingly. In this case, consumers are entitled to take it, free of charge, to municipal collection points or to a retailer

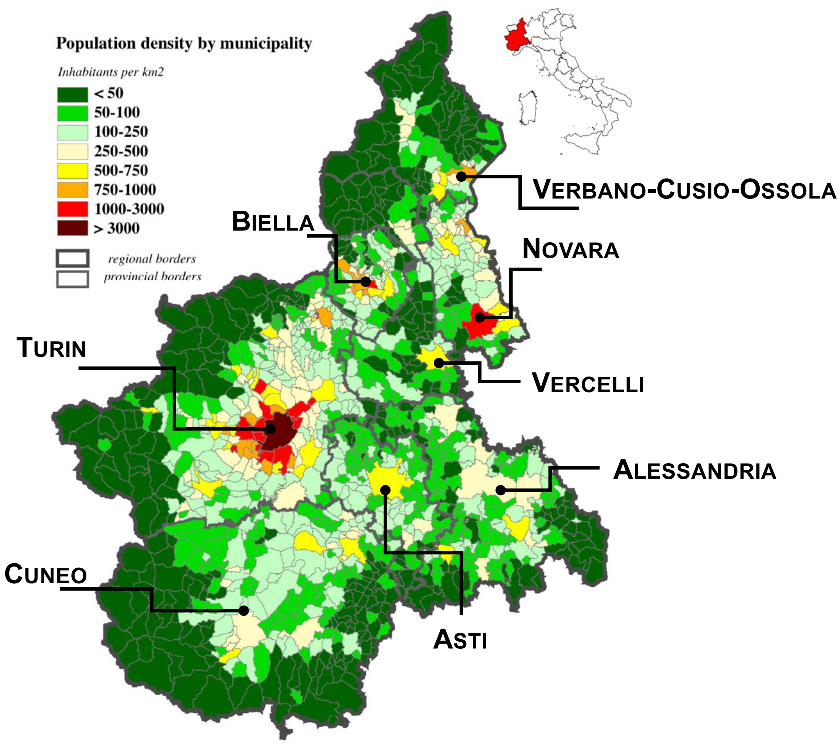

FIGURE 4 Population density by municipality in the Piedmont region. *Source*: www.arpa.piemonte.it.

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when purchasing a new, equivalent piece of equipment (One-for-One take-back) or to a retailer without making a new purchase, although this is only for small WEEE (One-for-Zero take-back). The consumer can only request free home collection for large WEEE (see Appendixes D and E for more details).

However, despite the presence of a large number of collection centres and a clear legislative framework regarding the disposal of electric and electronic goods, around 70% of domestic and professional WEEE is estimated to elude the formal WEEE management system in Italy, thereby further reinforcing the need for complementary management and valorisation systems of waste streams (CdC RAEE, 2023). Numerous stakeholders collaborate in ensuring the functioning of WEEE management and recycling operations (see Table F1). Some of these actors are active, especially near large urban centres, while fewer of these infrastructures exist in more peripheral areas, thus making it more likely that 'leakages' from appliances occur as a result of the inappropriate disposal of products.

3.2 | Data collection

The data collection for the in-depth case study of Astelav-Ri-Generation spanned from the launching of Ri-generation in 2016 to the year 2023. Multiple data streams and sources were utilised to understand the relevant dynamics, to increase and diversify the information base and to reduce biases and triangulate records in order to obtain an enhanced reliability and validity of the findings (Yin, 2017). The primary data collection took place between January 2019 and September 2023 (see Table G1 for the interview timeline and details on the informants). In the initial phase (January–April 2019), one author spent several days at Astelav collecting on-site archive material for an initial contextual reconstruction (history, organisation and geography) of the project implementation. To ensure narrative accuracy and validity, the authors discussed the findings with three senior informants in C-level roles. In a second phase (May 2019–October 2021), the data collection was focused on the local-level implementation of new remanufacturing practices—management and operations, investments, costs, logistics and supply-chain, skills and triple-bottom-line benefits—and on the role of Astelav, that is, its ICT architecture, database and warehouse management.

We first conducted 27 interviews with nine individuals from various hierarchical levels. This choice ensured exposure to diverse viewpoints, the mitigation of personal biases, the reduction of potential gaps in individuals' knowledge and the verification of information through the cross-referencing of different informants' input (Miller et al., 1997), as well as the granularity necessary for its analysis. The interviews adhered to a semi-structured, open-ended protocol, lasted 60–90 min, and were systematically recorded and transcribed. In the final phase (January 2022–September 2023), nine additional interviews were conducted with the same protocol to refine the results and address further questions that had emerged. In total, we conducted 36 interviews, thereby generating around 58 h of recorded content and 287 pages of transcription.

In addition, we gathered qualitative and quantitative data from publicly available secondary sources and internal documents, for a total of 553 pages (see Table G2), to complement the primary data from the interviews (Eisenhardt & Graebner, 2007).

3.3 | Data analysis

To address our research question, we employ an inductive approach that enables concepts and relationships to emerge from the data (Glaser & Strauss, 1967). We evaluate all collected data to ensure their appropriateness for our objectives, and to emphasise measurement validity and data coverage, as well as the suitability of the data for our research (Saunders et al., 2012). The analysis adheres to established guidelines for longitudinal case studies (Yin, 2017), and encompasses three phases.

In the first phase, we conduct a detailed reconstruction of the organisation's operations throughout the lifespan of Ri-generation. Employing multiple rounds of data coding, we identify patterns related to the enablers of remanufacturing practices, their implementation, and the strengths and weaknesses of this circular business model. We emphasise the challenges highlighted in Section 2.2 and depicted in Figure 2, as interpreted by our informants (Stake, 1995). These challenges were useful for the second phase of the data analysis, where we leverage on existing network models to design the most suitable logistics and knowledge-sharing remanufacturing system. We use the current remanufacturing model of Astelav-Ri-generation to hypothesise a new model in which the two companies would be unbundled and multiple remanufacturing labs, like Ri-Lab, would be created all over the region, according to the blueprint of our case study. We build our remanufacturing system by extending the circular business of Ri-Generation from the municipal level to full regional coverage and possibly to multiple regions throughout the nation.

To this aim, we code for Ri-generation's flows of goods and intangibles, the main actors responsible for them, and their triple-bottom-line benefits as a single business, and then, in combination with the regional analysis, the theoretical concepts and the circular network models from the literature, we analyse the remanufacturing value network and the opportunities. The objective was to partition the local territory into local units that business networks could manage. We explore various CE network infrastructures to address any tensions between the centralisation of certain activities (e.g., data management) and the operational decentralisation of others (e.g., remanufacturing activities), as discussed in Section 2.3. We specifically consider such configurations as star and hub-and-spoke frameworks, which facilitate a balanced centralised/decentralised system (Meng & Wang, 2011; Pels, 2020). These interconnected networks feature a central hub that serves as the focal point for resources, information and/or activity exchange, with multiple spokes coordinated by the hub and connected to peripheral points (Toh, 1984).

A minimum of two researchers simultaneously coded the data for all the primary and secondary materials, thereby ensuring a higher

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reliability as a result of the cross-checking of the previously coded text to maintain internal consistency (Miles & Huberman, 1994). We performed periodic comparisons between the researchers to validate the coding accuracy, and any discrepancies were resolved through discussions and occasional recoding. Subsequent interviews contributed to extending and revising our preliminary interpretations, which were consistently validated through contacts with Astelav and Ri-generation. Private secondary sources, such as internal archival sources, including annual reports and internal communication tools, played a pivotal role in corroborating the informants' recollections about the management's efforts to promote remanufacturing at the local scale.

Furthermore, on-site observation and informal conversations, in addition to the interviews, provided further insights which were used to hypothesise a regional remanufacturing system using a hub-and-spoke model. External archival sources, including the analysts' reports and business press, served as supplementary information on Ri-generation and, more broadly speaking, on regional WEEE management systems. We repeatedly updated and refined our emerging model by iterating between our empirical data and the emergent theory. Discussions with key informants were considered to support the validation of our interpretations (Lee, 1999) and contributed to the development of the regional remanufacturing system discussed in Section 4.

In the third phase, we estimate the annual resource savings of such an upscaled Ri-generation project through a back-of-the-envelope quantitative analysis, considering an average washing machine model and inventories of the material components (Enel, 2017). The average washing machine lifetime is 10 years, and remanufacturing can extend it to at least 15 years (see Appendix H for more on circularity). We began by examining Piedmont's 2022 official 'R2-Large household appliances' collection, which totalled 7,671,540 kg. Next, we consider different possible percentages of washing machines (WMs) within this category, from 20% to 80%. We computed the corresponding quantity of WMs in units, considering an average weight of 65 kg (RAEE, 2012). From this, we examine different possible shares of remanufactured WMs, ranging from 20% to 60%. Multiplying this value by the global warming potential (GWP) reference value of a WM (355 kg CO2eq, Yuan et al., 2016), we arrived at various potential scenarios of environmental benefits (expressed in GWP savings), which are presented in the Results section. For example, setting the percentage of WMs at 20% of the total R2 category resulted in 1,534,308 kg of WMs. Dividing this value by 65 yielded 23,605 units of WMs. Assuming 30% of those units underwent remanufacturing (7,081 units) and multiplying by 355 kg CO2eq resulted in a GWP savings of approximately 2.5 million kg CO2eq as a result of eliminating the production phase (Figure 5).

4 | RESULTS

In this section, we leverage on the insights from the Astelav-Ri-generation case study to build a framework for large-scale remanufacturing. Considering the theoretical models in the literature on CE networks discussed in Section 2.3, we identify a design for the remanufacturing system that addresses the observed bottlenecks while retaining the demonstrated strengths. We estimate the aggregate benefits this system could bring to the local ecosystem using regional data from Piedmont as an example. In the discussion section, we explore the features of our model that could be generalised to other regional contexts and the potential limitations for its application to different areas.

4.1 | A model for a large-scale remanufacturing system

The Astelav/Ri-generation case study confirms the technological and economic viability of the CE approach on a small scale, but also highlights its potential to scale the remanufacturing system to encompass a larger territory, by optimising the operations and societal benefits. Expanding the territorial coverage would extend the socio-economic and environmental advantages of remanufacturing beyond urban areas. Furthermore, capitalising on cost savings from scale and scope

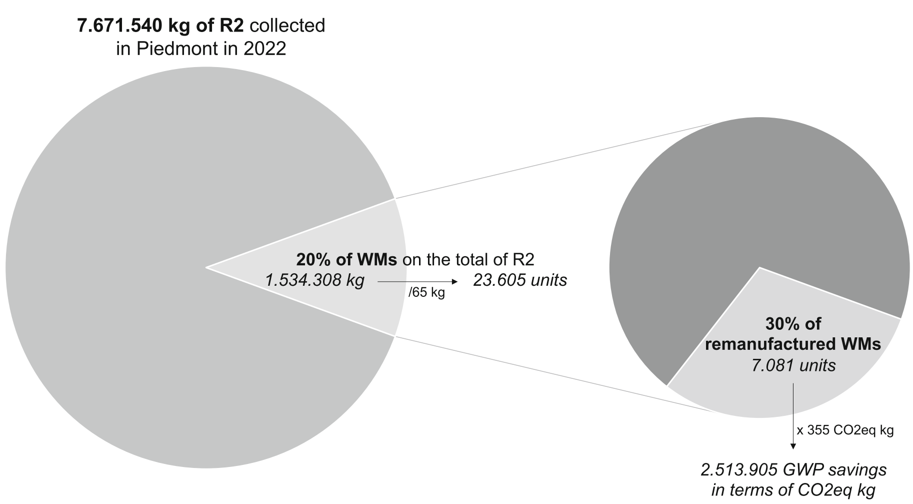

FIGURE 5 An example of estimating global warming potential (GWP) savings considering a specific percentage of washing machines (WMs) in relation to the total amount of R2 and, on this basis, the remanufactured WMs.

economies would enhance the financial sustainability of more complex remanufacturing practices.

We analyse the key characteristics of Astelav/Ri-generation that have contributed to its success in order to model a scalable remanufacturing system. Our case study reveals two critical features: first, Astelav, the large focal company, handles high-tech and scale-intensive tasks, such as the logistics management of spare parts, utilising advanced digital technologies, warehouse robotisation and predictive data analysis. Second, Ri-generation, the smaller entity, focuses on relatively low-tech remanufacturing practices at a flexible, small scale, by leveraging on individual repairers' expertise. The symbiotic relationship between Astelav and Ri-generation is vital, as Astelav utilises its digital and physical infrastructure to identify and provide cheap and rapidly available components, while Ri-generation connects with local stakeholders and sends detailed remanufacturing know-how back to Astelav.

An upscaled remanufacturing system should capitalise on the strengths of Astelav's high-tech tasks and Ri-generation's flexible low-tech practices, while addressing the current bottlenecks in scaling up to obtain a broader territorial coverage. An important consideration is connected to the geography of the companies: Astelav and Ri-generation currently share the same factory premises, which limits the capacity for territorial expansion to capture discarded appliances and satisfy consumers' demands. As previously discussed, the weight of remanufactured white goods makes distance a crucial cost component and a central bottleneck. However, a careful analysis of transport and logistics costs could envision a large-scale solution in which the two businesses could be spatially decoupled, which in turn would allow for a broader geographic coverage.

The remanufacturing lab developed in Ri-generation could be replicated in key hotspots around the territory, without any significant investments in physical capital, since most of the capital-intensive activities would remain in the parent company, which would continue to act as the leading high-tech hub. This approach minimises the transfer of heavy and bulky appliance goods for environmental and cost reasons; therefore, the optimal locations for remanufacturing laboratories in this regional ecosystem would depend on the proximity of the WEEE disposal centres and on the density of the local population, both of which should serve as proxies for the supply of used appliances and the demand for remanufactured ones. Instead, the flows of information and light spare parts that can travel over longer distances with lower financial and environmental costs could be centralised.

Additionally, in order to achieve a broader territorial coverage, this remanufacturing system could also be linked to individual local repair businesses, and in this way, it would be possible to reach more remote areas while relying on the infrastructure of the remanufacturing laboratories and thus, indirectly, on the focal company to lower the cost of their services and ensure the rapid provision of repair parts and components. Such a network of repairers could aid in advertising remanufactured goods, and in creating awareness and demand, while monitoring waste flows from peripheral locations. Supported by a focal company, this network could also assist in the proper disposal of informal WEEE, thereby reducing its quantity. Given that the repair activities primarily involve skilled tasks that are achievable through on-the-job training, these labour-intensive activities could serve as a source of inclusive employment, facilitated by knowledge exchanges and training with experts from the remanufacturing laboratory.

Table 3 summarises the key characteristics considered when designing our large-scale remanufacturing model and outlines the main flows managed by various actors in the remanufacturing system.

In our model, the first principle is to minimise the transport of used appliances, a goal that would be attainable thanks to the presence of numerous remanufacturing labs. Scale economies are relatively limited in remanufacturing labs, as flexibility in handling various brands and uncertainty about discarded product conditions reduce the opportunities for standardisation and mechanisation. Small to medium-scale labs would be sufficient: currently, Ri-generation employs 15 workers, but labs of fewer than 10 technicians could function well for areas with fewer appliances.

Although lighter for transport, spare parts represent a complexity in sourcing, due to the diverse array of component types on the market. Different brands of different vintages require different parts for replacement. Therefore, only a large company like Astelav could handle the complexity of supply chain logistics for spare parts. Although the spatial distance becomes less relevant for this activity and the company could be located virtually anywhere, the scale economies are significant: high-tech solutions for warehouse storage and robust supply networks that cover a wide range of product codes are essential for the cost-effective sourcing of spare parts, which makes the remanufacturing process financially viable. This large, innovative and highly competitive company could serve remanufacturing labs on a regional scale and possibly even across multiple regions, by leveraging on increasing economies of scale.

TABLE 3 The flows of goods and intangibles and the main actors and factors responsible for them.

Flow	Type and weight	Distance	Actor	Scale economies	Optimal location	Size of the involved actors
Discarded appliances	Physical, heavy	Short	Remanufacturing labs	Minimal	Nearby WEEE and nearby customers	Medium
Spare parts	Physical, light	Long	Focal company	Significant	Anywhere	Large
Remanufacturing information	Immaterial, weightless	Any	Repairers, remanufacturing labs	None (or even diseconomies)	Spread throughout the territory	Small
Predictive information	Immaterial, weightless	Any	Focal company	Significant	Anywhere	Large

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The information and knowledge flows in this remanufacturing system come in two types: tacit knowledge and predictive knowledge. Indeed, repair know-how, which is primarily embedded in human capital, can be handled by repairers and the remanufacturing lab personnel. This tacit knowledge is challenging to formally codify and can be disseminated across the territory through direct knowledge transmission via apprenticeships. Excessively large units might encounter scale diseconomies, if specialised information about such repairs is better acquired on a one-to-one basis. The key advantage of this tacit knowledge is that it allows multiple types of damage to be handled through expertise and practice. On the other hand, predictive knowledge regarding the most frequent breakdowns is a data-driven process in which advanced digital competence and data infrastructures are crucial. Hence, predictive information on the demand for components and data aggregation from repairers and remanufacturing labs should be managed centrally on a large focal company platform.

The flow characterisation shown in Table 4 establishes the design boundaries of our large-scale remanufacturing system. The main tension is between achieving scale economies, an efficient management of spare parts from multi-product supply chains, and high-quality data management regarding all the components versus the need for good territorial coverage in the presence of heavy appliances with high transport costs. Considering the various CE network infrastructures discussed in Section 2.3, the configuration that best aligns with the requirements described above—a strong central company and numerous widespread smaller ones—is a star or hub-and-spoke network. Our analysis suggests a hub-and-spoke model with two different tiers as a suitable design to address these challenges. Such models, which

TABLE 4 Global warming potential saving scenarios: The example of the Piedmont region (Italy).

Total R2 collected in Piedmont in 2022 (kg)				**7,671,540**				
		% of washing machines (WMs) on the total of R2						
		20%	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
Kg of WMs		1,534,308	2,301,462	3,068,616	3,835,770	4,602,924	5,370,078	6,137,232
Units of WMs		23,605	35,407	47,209	59,012	70,814	82,617	94,419
% of remanufactured WMs	*20%*	4721	7081	9442	11,802	14,163	16,523	18,884
	30%	7081	10,622	14,163	17,704	21,244	24,785	28,326
	40%	9442	14,163	18,884	23,605	28,326	33,047	37,768
	50%	11,802	17,704	23,605	29,506	35,407	41,308	47,209
	60%	14,163	21,244	28,326	35,407	42,489	49,570	56,651
		GWP savings in terms of CO2eq (KG)						
% of remanufactured WMs	*20%*	1,675,936	2,513,905	3,351,873	4,189,841	5,027,809	5,865,778	6,703,746
	30%	2,513,905	3,770,857	5,027,809	6,284,762	7,541,714	8,798,666	10,055,619
	40%	3,351,873	5,027,809	6,703,746	8,379,682	10,055,619	11,731,555	13,407,491
	50%	4,189,841	6,284,762	8,379,682	10,474,603	12,569,523	14,664,444	16,759,364
	60%	5,027,809	7,541,714	10,055,619	12,569,523	15,083,428	17,597,333	20,111,237
Total R2 collected in Piedmont in 2022 (kg)				*7,671,540*				
		% of washing machines (WMs) on the total of R2						
		20%	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**
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	GWP savings	*1,675,936*	*2,513,905*	*3,351,873*	*4,189,841*	*5,027,809*	*5,865,778*	*6,703,746*
	30%	7081	10,622	14,163	17,704	21,244	24,785	28,326
	GWP savings	*2,513,905*	*3,770,857*	*5,027,809*	*6,284,762*	*7,541,714*	*8,798,666*	*10,055,619*
	40%	9442	14,163	18,884	23,605	28,326	33,047	37,768
	GWP savings	*3,351,873*	*5,027,809*	*6,703,746*	*8,379,682*	*10,055,619*	*11,731,555*	*13,407,491*
	50%	11,802	17,704	23,605	29,506	35,407	41,308	47,209
	GWP savings	*4,189,841*	*6,284,762*	*8,379,682*	*10,474,603*	*12,569,523*	*14,664,444*	*16,759,364*
	60%	14,163	21,244	28,326	35,407	42,489	49,570	56,651
	GWP savings	*5,027,809*	*7,541,714*	*10,055,619*	*12,569,523*	*15,083,428*	*17.597.333*	*20.111.237*

Note: In the analysis, colours were employed to differentiate the various percentages of remanufactured washing machines in the rows. Additionally, the gradient of the same colour, ranging from lighter to darker shades, was used to indicate the increasing percentage of washing machines within the total count of R2 units in the columns.

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are commonly applied in complex transportation and logistics contexts, account for the necessity of centralising certain operations while extending services over a large geographic area. In our setting, we have developed a two-tier spoke model in which the remanufacturing centres and individual repairers can operate at a distance from the central hub but closer to WEEE flows and customers, as illustrated in Figure 6.

The system's hub centralises the management of spare parts through an advanced digitised supply chain management. The spokes in the first tier perform full-fledged remanufacturing activities in more densely populated areas where there is a higher supply and demand for second-hand appliances. Simultaneously, a network of repair technicians in the second tier extends to less densely populated areas, and assists customers in disposing of or replacing their used appliances. The number of spokes could vary on the basis of the economic conditions and ecosystem needs over time, since the investment necessary to open a new remanufacturing lab is relatively small, with fixed costs that are primarily associated with equipment and the training of technicians and with the link to the central hub to provide cheap parts and components. In this system, used products are repaired and resold locally, with only spare parts being transported over longer distances.

4.2 | Estimation of the benefits

The benefits of the hub-and-two-level spoke model presented in the previous section cover the whole spectrum of triple-bottom-line benefits from circular business models. We here outline their qualitative features and subsequently offer numerical examples from the Piedmont region to provide an order of magnitude of these effects.

From an environmental point of view, this remanufacturing system leverages on the local CE to reduce the use of raw materials and energy needed to manufacture new products; it delays and ultimately reduces the amount of e-waste destined for landfills and minimises the risks of environmental toxicity from mismanaged waste streams; it mitigates the pollution associated with the long-distance transport of appliances, as it keeps them within the local business ecosystem, even in regions that lack the manufacturing capacity for new large appliances.

From the social point of view, this system presents an inclusive approach to CE, which may disrupt part of the sales of large manufacturing brands but, at the same time, enhances local employment and upskilling in the labour-intensive activities of the remanufacturing labs and repairers' businesses. The Ri-generation case has

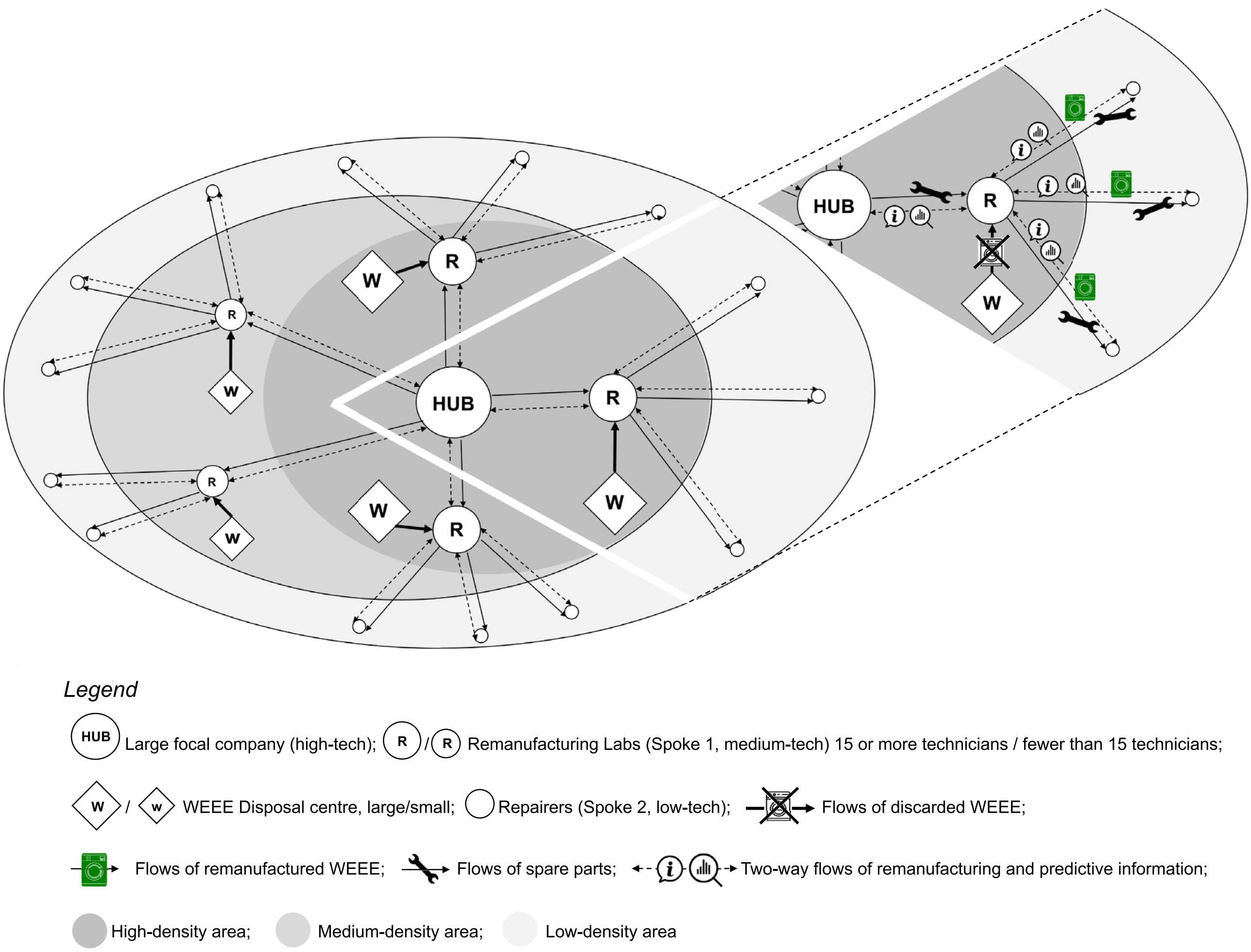

FIGURE 6 Hub and two-level spoke regional remanufacturing system. The darker shading represents areas with a higher demand density.

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already demonstrated the applicability of an inclusive workforce in remanufacturing labs, as the transferability of repair knowledge does not necessitate any prior education. Moreover, the system enhances social equity on the market, as it involves selling remanufactured products at a substantial discount and making high-quality home appliances more affordable for the local population.

Finally, although some environmental and social benefits could already be achieved with a smaller system at the municipal level, such as Astelav/Ri-Generation, the economic feasibility of the system drastically increases when regional upscaling is introduced. Strategically locating remanufacturing labs throughout the territory would minimise the transport costs from WEEE centres; access to more diversified waste streams across a region would ensure the availability of used appliances; a wider territorial coverage would broaden the range of repairs and create synergies between the remanufacturing centres and scope economies, as well as the learning and fine-tuning of repair knowledge over time, especially when the data are processed centrally to create predictive models of frequent malfunctions. Scaling up would enable the development of standardised repair services, thereby providing customers with a basic set of components for preventive maintenance and ensuring the replacement of parts subject to frequent wear and tear. Purchasing frequently needed parts in bulk would allow additional scale economies to be achieved through volume discounts and reduced transaction costs.

Although the discussed benefits already present a positive outlook for this large-scale remanufacturing system, it is essential to provide quantitative estimates for a comprehensive understanding of the system. Therefore, we have estimated the indicative environmental, economic and social spillovers that this circular remanufacturing system for appliances could bring about in the case of Piedmont—where Astelav-Ri-generation currently operates. Although the model has been applied to Piedmont, it could be adapted to other regional contexts, since the distance between the central hub and the spokes can be considerable. Policymakers interested in applying this remanufacturing system locally should calculate similar environmental and socio-economic metrics that are relevant to their regional context. Figure 7 summarises the key data points pertaining to the benefits of remanufacturing at the municipal scale, which could then be scaled up to cover the entire region.

Table 4 presents some potential scenarios of the GWP savings that could result from eliminating the production phase of a new washing machine through the remanufacturing an old one, as explained in Section 3.3. It is possible to see that the environmental benefits of a large-scale remanufacturing model, in terms of CO2 reductions, are quite sizeable, and these scenarios probably represent a conservative estimation (e.g., they do not include the savings in transport emissions resulting from the shorter distances travelled by second-hand washing machines) and do not include other environmental spillovers.

5 | DISCUSSION

The presented analysis proposes a macro-level remanufacturing model that leverages on scale and scope economies, while mitigating the complexities of a broader spatial coverage of transport and logistics. Our model illustrates the synergy between a central hub that manages all the key activities—supply chain logistics, data integration and analysis, market analysis and forecasting—and two tiers of decentralised units that are responsible for remanufacturing and repair operations—e-waste collection, remanufacturing, repairs and final appliance sales. The business case analysis and its regional

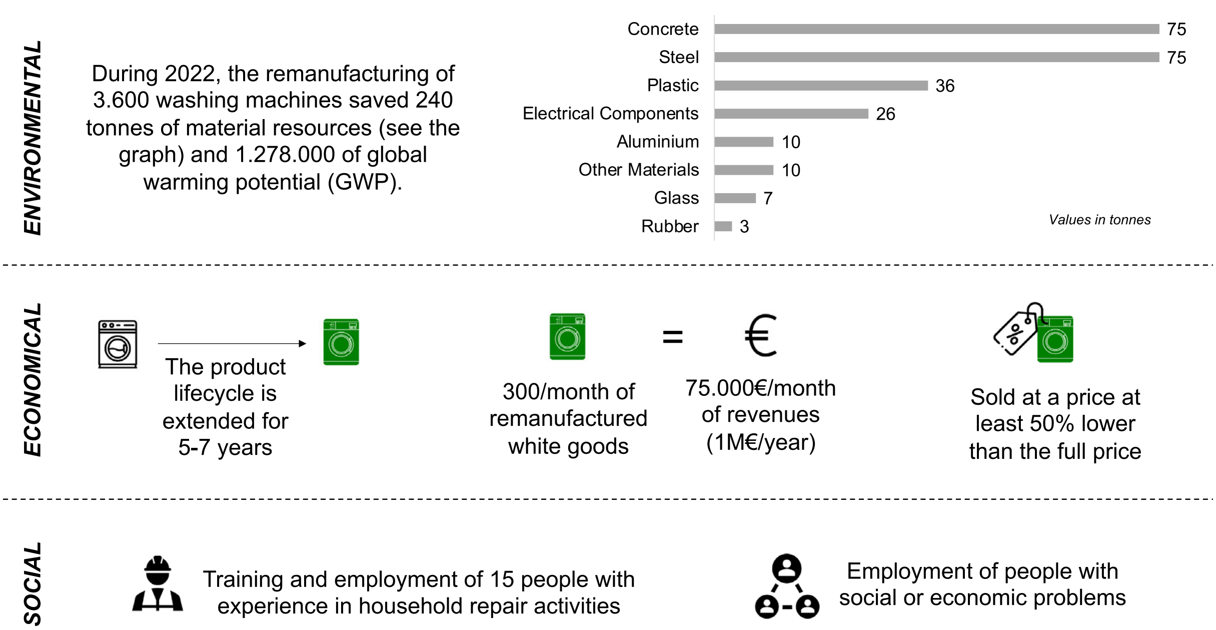

FIGURE 7 Economic, environmental and social benefits after remanufacturing at the municipal scale in Turin (Italy)—adapted from (Enel, 2017).

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contextualisation have highlighted the importance of the central hub as an efficient large-scale spare parts dealer, given the inherent complexity of the supply chain of appliance components, due to the variety of spare parts with different obsolescence and intermittent demand patterns that complicates stock control strategies and forecasting.

Our findings indicate that the transition to an integrated, systemic, centralised/decentralised CE model could be grounded on the upscaling of a sustainable business model within a 'star-type' hub-and-spoke network structure (Kim & Zhang, 2008). Although our findings are based on an inductive analysis of a specific business case and its regional context, the principles could be adapted to other territorial characteristics, while retaining the key insights of our exploration. The specific interactions between the hub and its spokes may vary on the basis of the business ecosystem of a territory. For instance, the central hub could manage the remanufacturing lab franchising or participate in a cooperative of small independent remanufacturers. The affiliated individual repairers could be lab employees, autonomous workers, or even individual traders with small shops. However, apart from the specific contractual agreements between parties, certain key features characterise our model, regardless of the location of the application, and can provide interesting theoretical and practical insights. Thus, some general propositions have been derived from our analysis, our main theoretical and practical contributions have been discussed, and the limitations of our results have been presented.

5.1 | Propositions

Building on our previous results, we formulate three propositions that capture the main elements of our remanufacturing system and which could be investigated in other contexts in future research.

First, we underline the importance of distinguishing data that can be standardised, collected in the central hub and used to generate predictive knowledge from the technical know-how embedded in the human capital of experienced technicians that is best transferred through one-on-one interactions. A well-designed system shares and exploits the complementarities between the two types of knowledge. Big data analytics is the fundamental prerequisite for the viability of a successful system that requires a systematic collection and sharing within the supply chain to derive insights regarding remanufacturing times, costs and spare parts. From this standpoint, we suggest the following proposition:

> **P1.** A large-scale remanufacturing system should organise knowledge, data and information flows according to their transferability across individuals and platforms. Tacit repair expertise and know-how should be diffused in small centres spread throughout the territory; conversely, big data analytics about parts and markets should be centralised and shared within the supply chain to leverage on scale economies in data management.

Second, we highlight the key elements necessary to manage the physical flow of goods and the location of physical infrastructures. Organising this remanufacturing system according to an optimal transport logic minimises the costs and reduces pollution from the movements of heavy objects. Minimising the transportation of large appliances underscores the importance of situating remanufacturing operations in proximity of the collection centres. Simultaneously, the feasibility of establishing multiple spare parts warehouses is contingent upon the nuanced assessment of geographical considerations that necessitate centralisation. This is particularly true of the complex sourcing challenges associated with components, whereby the producers of spare parts are frequently situated in distant continents and thus pose difficulties in traceability. In this context, our emphasis is directed towards advocating the restructuring of the supply chain and the strategic relocation of operational activities. On the basis of the above discussion, we suggest the following proposition:

> **P2.** A large-scale remanufacturing system should organise the flows of physical goods according to their weight and bulkiness. Minimising the transport of large appliances requires that the remanufacturing labs should be close to waste collection centres and the potential customers. Conversely, spare parts and components can travel long distances, thus the central hub can be located wherever it is suitable to have its physical infrastructure.

These two propositions also represent general principles that are applicable in the context of other network structures: if a different region from Piedmont were to implement another system design (for instance, centred around two hubs to increase resilience to supply chain shocks), these principles should still be considered.

Finally, we emphasise the geographic logic behind our model: the three levels proposed in our model capitalise on the centralisation of high-tech tasks in the hub, and on moving to more remote areas for increasingly low-tech solutions. The symbiotic linkages between hub-and-spokes make this solution financially, ecologically and socially sustainable. The hub-and-spoke model is a distribution system that is particularly useful to address the tensions that stem from the need to centralise managerial activities (e.g., data management) and the concurrent decentralisation of operational activities (e.g., remanufacturing at a large scale). The assumption underlying this proposition, which also determines its generalisability, is that the hub is sufficiently reliable to not require any redundancy of its operations (as in our case study): indeed, a critical requirement of star and hub-and-spoke networks is the necessity of always having the central hub performing its functions, which leads to the risk of having to shut down the whole system if there are any disruptions in the centre. Furthermore, the success of a regional remanufacturing system is contingent upon the integration of entities characterised by varying dimensions and roles within a network paradigm. This entails specialised spokes tasked with the meticulous screening and remanufacturing of recoverable products, while concurrently directing discarded products beyond

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their remanufacturing capacities to higher tiers. We thus suggest the following proposition:

> **P3.** A large-scale remanufacturing system, shaped as a star network, leads to integration and synergy between centralised high-tech solutions in a core company (hub) with decentralised remanufacturing labs and repairs (spokes), and to the spread of triple-bottom-line benefits over the local ecosystem.

In this regard, establishing standardised rules and incentives becomes imperative to foster the creation of spokes, where procedures, activities and training are homogenised. This strategic standardisation is aimed at maximising the remanufacturing of discarded products, and at only directing those items deemed indispensable for further processing to higher tiers. In this sense, laboratory technicians and small repairers living in less populated areas would no longer need to travel to large urban centres but could remain in the local territory and carry out their activities without any significant investments, given the extant support facilitated by the central hub. Specifically, it would no longer be necessary to perform production planning and control activities at the local level (Butzer et al., 2016; Gallo et al., 2012)—as they would now be centralised in the high-tech hub – and this would allow the remanufacturing and repair activities to be carried out more efficiently and flexibly. The latter results from the structure of the model, where agile, decentralised spokes rely on the volume of the received discarded products and do not require production programming.

Our analysis is rooted in the business case under examination and its regional context, and its extrapolation to other markets or areas should therefore be conducted carefully. For example, in the context of multiple mega-cities, it might be necessary/possible to have multiple hubs and a different network structure to cover the entire territory. Nonetheless, the theoretical and managerial implications that derive from our investigation can be used to inform a broad spectrum of actors involved in the development of CE ecosystems. We discuss these aspects in the next paragraphs.

5.2 | Theoretical and practical contributions

Considering the three main findings of our study, it is possible to derive the related theoretical and practical contributions. First, by modelling *a large-scale system for the sustainable remanufacturing of WEEE*, we combine the literature on CE and network topology. This intersection provides a solid theoretical foundation for scaling up circular strategies at the macro level, considering the trade-off between efficiency, sustainability and territorial coverage. By adopting this integrated perspective, we have successfully devised operational and strategic mechanisms (Pesce et al., 2023; Xia et al., 2022) that are fundamental to bridge economic approaches that consider the costs and selling prices of remanufactured products (Jiang & Zheng, 2022; Neto et al., 2016; Jochen, 2015), with managerial perspectives that model how to strategically organise resources, know-how, skills and flows of products and information into a remanufacturing large-scale structure (Tonelli & Cristoni, 2019; Xia et al., 2022). Moreover, we incorporate firm-level insights within more complex circular local systems (Geissdoerfer et al., 2023; Hofmann & zu Knyphausen-Aufseß, 2022) to propose innovative, scalable solutions that effectively tackle the bottlenecks faced by individual companies operating on a smaller scale, thereby facilitating expansion for a broader territorial coverage.

From a practical viewpoint, overall, we have broadened the research scope of circular business models towards an ecosystem perspective that includes multiple stakeholders (consumers, local retailers, public service operators, etc.) and not only a company-centric viewpoint (Alblooshi et al., 2022; Tapaninaho & Heikkinen, 2022), thus enlarging the scale and widening the scope of remanufacturing, in terms of positive impacts on the territorial coverage (Bressanelli et al., 2019b; Goodall et al., 2014). Our model has the potential to guide both focal companies, with the aim of expanding their circular business models within a regional territory, and small repair/remanufacturing centres. For the latter to remain competitive, it would be beneficial for them to not operate individually but to revolve around a larger company that is capable of efficiently sourcing parts and components and creating networks within the territory. A point of connection between these two actors lies in the expertise required for the remanufacturing process and forecasting the necessary spare parts that have to be stocked. In this sense, the exchange of knowledge should occur bidirectionally: on the one hand, the focal company could impart knowledge to small repairers/remanufacturers, thus attracting them into its sphere; on the other hand, these smaller entities, by providing information on the type and frequency of faults, could enrich the database of the focal company to obtain increasingly accurate forecasts.

Second, we have modelled our remanufacturing system on *large appliances*, one of the most problematic categories of WEEE, in terms of lifecycle extension and remanufacturing, thus theoretically contributing to addressing the challenges related to their transportation (due to their size and weight) and disassembly (due to the high number of components), both of which require complex logistics and advanced know-how (Li et al., 2013; Scarpellini et al., 2019; Wang & Wang, 2019b). From a practical standpoint, our model could also be generalised to heavy and complex products composed of numerous electronic and non-electronic components and thus be relevant by demonstrating that the CE can be extended beyond small products (e.g., mobile phones) and less sophisticated items (e.g., tables) to include complex and high-tech products. In this sense, we highlight how remanufacturing conserves not only the materials but also the 'embodied energy' of the original manufacturing processes, thereby enabling the substantial retention of value from used products by prolonging the products' lifespan (Nasr, 2019).

Third, by characterising the *triple-bottom-line benefits* of the regional remanufacturing model, we have addressed the theoretical lack of investigation and quantification of the systemic benefits of CE in the WEEE industry, thus exploring the macro implementation of CE models (Scarpellini et al., 2019). In practice, building such a system at the macro-level (e.g., encompassing an entire region) would

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improve its financial viability thanks to significant scale and scope economies. Moreover, innovative digital technology applications can enable a more efficient organisation of the remanufacturing value chain to create a brand new 'second life' market for high-quality appliances with cheaper products for local customers. Entrepreneurs interested in setting up or participating in a remanufacturing system for appliances could contribute to the realisation of hubs or spokes, on the basis of their capacity to build supply chain networks for spare parts and the industrial infrastructure needed for the central warehouse or the decentralised remanufacturing labs. However, in parallel, support from local policymakers to the local entrepreneurs would be beneficial to coordinate the different stakeholders in the system and to finance its initial development, in order to enhance opportunities to replicate this remanufacturing model in new locations.

5.3 | Limitations and future research

Our model presents some limitations, given the ambitious nature of the proposed remanufacturing system. First, the quantitative estimates of environmental benefits are indicative and are based on a wide range of different scenarios for only one specific region, because some information—such as the actual number of washing machines in Piedmont and which of these are potentially regenerable—is not known. This quantification exercise should be considered just as a broad indication of some of the magnitudes of the benefits that could be achieved, and not as a precise accounting of guaranteed outcomes. Second, the elasticity of demand for regenerated products is uncertain, and to estimate such a demand would require a full analysis of the evolution of consumers' preferences for remanufactured products. We assumed that such a demand is not a bottleneck for our large-scale remanufacturing system, but future research should characterise the demand elasticity for these recovered goods more precisely. Third, the existing remanufacturing processes are not currently at their maximum efficiency for large-scale operations, and process innovations could lead to further productivity improvements (e.g., digital technologies to support the sorting and selection of discarded appliances).

Our hub-and-spokes model focused on used home appliances, but further research is needed to model circular large-scale ecosystems in other sectors. According to the European Remanufacturing Network, by 2030, the remanufacturing market in Europe will be worth 100€ million and will involve such industries as aerospace, automotive and machinery and equipment goods (Parker et al., 2015). These sectors present some characteristics that are similar to those examined in our model, in terms of flows of physical parts and data, but their technology and supply chains might present other specificities. Further research is needed to determine whether a hub-and-spokes model would also apply to these other sectors. Moreover, an interesting avenue for further study is the role of consumers on these remanufacturing markets: the evolution of the demand, in both the context of appliances and for other remanufacturing goods, with possibly greater sensitivity to the environmental features of their purchases, can play a significant role in driving the shape that these circular systems can take in a different context (Hunka et al., 2020).

It is also essential to acknowledge and critically examine the potential negative impacts and trade-offs associated with the proposed system. One significant issue that is unavoidable in remanufacturing processes is that such products may not exhibit the same level of efficiency as new products. Advances in technology mean that new products are often designed to be more energy- or water-efficient, thereby reducing their overall environmental footprint. In contrast, remanufactured products, despite their extended lifespan and reuse of materials, may consume more energy, water and/or detergents during the remaining life cycle, if the original appliance used relatively older technological settings, thereby diminishing the net environmental benefits (Huether et al., 2022). To partly mitigate this issue, remanufacturing companies could adopt strategies that involve selecting discarded products on the basis of their age and current efficiency rating. For example, the remanufacturing labs could focus on products that are no older than 10 years and have an energy efficiency rating of at least B. Moreover, the remanufacturing process itself is resource and energy-intensive (Dahm, 2022) as the disassembly, cleaning, remanufacturing and reassembly of products require substantial amounts of energy and, in some cases, materials. These inputs can offset some of the environmental gains obtained by extending the lifecycle of a product and diverting waste from landfills. Future research could employ a Life Cycle Assessment (LCA) to comprehensively evaluate the environmental impacts of remanufacturing processes, thereby offering more detailed insights into the involved net benefits.

Additionally, a core criticism of circular remanufacturing systems is that they frequently require more complex logistics and transportation, which result in additional pollution and emissions. This trade-off presents a significant challenge for large and heavy appliances, as the environmental benefits of remanufacturing can be offset by the increased emissions and energy use associated with more complex and extended supply chains (Llorach-Massana et al., 2015). Nevertheless, one of the key points in our hub-and-spoke model is the minimisation of the transport of large appliances as a result of the situating of the remanufacturing labs near collection centres and customers in order to reduce the environmental impact of logistics. Although this solution may not completely overcome the limitations of the increased complexity of circular systems, it is a step further in addressing such challenges. Overall, these benefits and drawbacks are not mutually exclusive and should be carefully weighed through specific logistics studies or simulations considering different scenarios, including the transport phase, to understand the overall impact of remanufacturing on sustainability.

Finally, the traditional business model of individual ownership, in which each household has its own washing machine, should not be presumed to be the only viable business model when approaching sustainability solutions for large household appliances (Hofmann, 2019). Alternative circular business models, such as shared usage schemes—from classic communal laundries to digitally enabled pay-per-service leasing arrangements (as developed, for instance, by companies like Bundles and Homie)—have the potential to decrease the total number of required machines, thereby reducing the overall environmental burden. In these alternative models, the producers retain ownership of the washing machines during the use phase, and

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thus have a further incentive to ensure reparability and durability of the products. Although classical solutions, such as laundromats, may not be applicable for all kinds of white goods (e.g., the shared use of fridges or ovens is currently very unusual), rental pay-per-use solutions have a broader range of applicability and can offer environmental benefits that could be complementary to remanufactured products. However, to date, these new business models have not been studied in combination with remanufacturing systems, and they could thus represent an interesting avenue for future research.

6 | CONCLUSIONS

This paper examines the role the private sector plays in developing large-scale circular systems to manage WEEE in the appliance industry. We have explored how an integrated remanufacturing system can be implemented at a macro/regional level to spread its triple-bottom-line benefits. Starting from a real remanufacturing business operating at a small scale, we have developed a model for a hub-and-spoke circular ecosystem characterised by a high-tech central hub and two levels of spokes. The former performs the remanufacturing activities in 'labs' that are specialised in industrially recovering used appliances, while the latter level reaches the most remote areas of the territory through the use of individual repairers and small repair businesses that directly serve individual clients. This model reduces the distance the heavy goods (discarded and remanufactured appliances) have to travel, enables a widespread territorial coverage and favours the exchange of know-how and data-driven information among the stakeholders of this circular ecosystem.

In our model, advanced technologies and human capital can work hand-in-hand to enable better remanufacturing systems that are able to overcome the bottlenecks of supply chains pertaining to the sourcing of spare parts, to organise the logistics of their provision and storage, and to deliver them throughout the territory so that they can be repaired and remanufactured as close as possible to the actual WEEE. The current policies mandate the centralisation of discarded products in a few large landfills to prevent the spread of their environmental pollution. Any entity willing to remanufacture such goods will need to establish an efficient take-back system and the capacity to select only goods with a high likelihood of successful remanufacturing to avoid excessive replacement costs. Although waste centralisation ensures control, it complicates the process, as the discarded/remanufactured products have to travel twice—from the territory to the landfill and then back to the territory. In this regard, the need for multiple collection points throughout the territory, coupled with closer remanufacturing centres, becomes evident to minimise transportation costs and the environmental impact. We argue that certain policies can favour the development of such a remanufacturing system, and support changes in the actors, roles and regulations to operate at various intervention levels. The current regulations lag behind from the technological availability point of view, thereby hindering the deployment of the most innovative remanufacturing solutions.

A variety of policy initiatives could support the development of the system we have proposed in our study, even as part of broader policy frameworks, such as the European Union's Circular Economy Action Plan (CEAP). One of the easiest solutions to promote the development of this second-hand market would be the elimination of VAT taxes on second-hand remanufactured products (which, in Italy, is set at 22%) since the tax would already have been paid on the first 'life' of the product. In this way, customers would be incentivised to buy remanufactured products instead of new ones. Moreover, policies that enhance transparency and awareness of the repairability of electronic goods are also fundamental to support the development of this circular industry. In this sense, the Sustainable Products Initiative within CEAP clearly supports eco-design for disassembly and reparability, especially in key sectors such as electric and electronic goods. In this vein, individual countries have adopted national laws on consumers' right-to-repair and developed reparability indexes which should encourage the production of products that are more easily disassembled and adjusted. From a social perspective, incentives for upskilling training courses throughout the territory could be an efficient investment to develop remanufacturing skills and engage people from a young age. Such skills could be enhanced by innovation policies aimed at facilitating the adoption of breakthroughs in key technologies pertaining to damage detection (such as the Internet of Things, Radio Frequency Identification) and disassembly activities (such as Augmented and Virtual Reality, Collaborative Robots) and at monitoring the sold remanufactured products (Ondemir & Gupta, 2014; Wang & Wang, 2019b).

In conclusion, this article proposes a CE framework that can be used to build a large-scale remanufacturing system that could operate at the regional or cross-regional level. This remanufacturing system could be a game changer for circular business models: throughout most of the recent history of humans, cheaper products have always been economically beneficial for consumers but have also come with a high hidden cost for the environment and society. In order to keep electronics affordable, the price tag of new products has never included the environmental externalities or exploitative labour practices behind such products. The remanufacturing system modelled in this paper, instead, introduces a strategy that could be adopted to sell cheaper products on the local market but with substantial additional environmental and social benefits. Policymakers should consider this as a true win-win-win solution to start building a circular economy.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interest.

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APPENDIX A: LITERATURE REVIEW

TABLE A1 Detailed summary of the relevant literature at each of circular economy levels.

Circular economy levels		Topic of the papers	References
MICRO LEVEL	The micro level does not consider interactions outside of the firm and rather focuses on the actors that perform the remanufacturing activities. Several studies analyse the different approaches of original equipment manufacturers (OEMs) or third-parties. This literature finds that the incentives for OEMs to engage in remanufacturing are often shadowed by concerns about limited circular competencies and by the risk of cannibalising their own new products, while for third parties it is easier to engage in remanufacturing as a stand-alone activity that opens new market opportunities in a specific niche. The micro-level literature, however, does not integrate these firm-level insights into more complex circular local systems.	Vogt Duberg et al. (2020) identified the essential and support factors that OEMs must consider when transitioning part of its business to remanufacturing	(Vogt Duberg et al., 2020)
		Jensen et al. (2019) explored the development of remanufacturing activities in OEM businesses to assess if remanufacturing activities can spur sustainable business innovations	(Jensen et al., 2019)
		Berssaneti et al. (2019) identified the variables related to value generation in the reverse logistics of electronic products from the perspective of third-party companies	(Berssaneti et al., 2019)
		Vogt Duberg et al. (2023) proposed a 5-step approach to describe a remanufacturing initiation for OEMs	(Vogt Duberg et al., 2023)
		van Loon et al. (2022) discussed the development of circular business models for a large white goods manufacturer, in particular the shift from selling washing machines to repeated leases with remanufacturing steps in-between	(van Loon et al., 2022)
	At the micro level we find the majority of studies specifically on remanufacturing: This research concentrates on quantitative analyses regarding the optimal price and quantity, the viability, feasibility and economic convenience of remanufacturing. Overall, these studies show that, for remanufacturing to be a financially viable process, it requires careful design of supply chains and operations, since in many cases linear processes using virgin raw materials are cheap and easier to organise.	Li et al. (2017) studied the optimal price and production quantity of new and remanufactured products with a two-stage model under both scenarios under which the remanufacturing is conducted by the OEM or by the third-party remanufacturer	(Li et al., 2017)
		Reimann et al. (2019) focused on the link between remanufacturing and the opportunity to lower the variable remanufacturing cost via process innovation	(Reimann et al., 2019)
		Goodall et al. (2014) identified tools and methods which have been developed within academia to support the decision process of assessing and evaluating the viability of conducting remanufacturing, and evaluate how they have met the requirements of the decision stage	(Goodall et al., 2014)
		Farahani et al. (2019) studied the remanufacturing processes of reusable products and parts, cost and demand of remanufactured products and parts to determine return quality thresholds during multiple production period	(Farahani et al., 2019)
	In a broader circular business model perspective, several studies examine specific case studies at the company level.	Whalen (2019) analysed three types of Extending Product Value business models and presenting their resource efficiency contributions	(Whalen, 2019)
		Van Loon and Van Wassenhove (2020) described the initial ideas of four companies on how the circular business model should be designed, the process	(van Loon & Van Wassenhove, 2020)

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TABLE A1 (Continued)

Circular economy levels		Topic of the papers	References
		they went through, challenges faced, and the eventual outcome	
		Pollard et al. (2021) developed and refining a Circular Economy Business Model Innovation Process Framework	(Pollard et al., 2021)
		Veleva and Bodkin (2018) demonstrated that there are emerging opportunities for small companies with innovative business models to enter the market and advance product end-of-life (EoL) management	(Veleva & Bodkin, 2018)
		Boustani et al. (2010) and Bressanelli, Saccani, Perona, and Baccanelli (2020) focused specifically on the household appliance sector, evaluating the energy and economic consequences of appliance remanufacturing relative to purchasing new products, and an exploration of multiple case studies on how circular economy practices have been adopted in some companies of the household appliance industry	(Boustani et al., 2010; Bressanelli, Saccani, Perona, & Baccanelli, 2020).
		Geissdoerfer et al. (2023) conducted an exploratory case study on the drivers and barriers for the different type of circular business model innovation (i.e. circular start-ups, diversifying or transforming their BM towards the CE or acquiring external CBMs)	(Geissdoerfer et al., 2023)
		Hofmann and zu Knyphausen-Aufseß (2022) examined the organizational capabilities needed to orchestrate CBM experiments, drawing on a systematic within- and cross-case analysis with two different firms	(Hofmann & zu Knyphausen-Aufseß, 2022)
		Barreiro-Gen and Lozano (2020) analysed how organizations have implemented the four Rs (reduction, repairing, remanufacturing and recycling), finding that organizations focus on reducing and recycling more than on repairing and remanufacturing	(Barreiro-Gen & Lozano, 2020)
		Linder and Williander (2017) examined the challenges of circular business models implementation based on remanufacturing and reuse.	(Linder & Williander, 2017)
		Sundar et al. (2023), analysed and identified the barriers that hinder the implementation of CE in household e-waste management by reviewing the existing literature	(Sundar et al., 2023)
MESO LEVEL	At the meso level, there is a variety of models for industrial symbiosis, connecting companies and other stakeholders to enhance circular economy actions, and some of these studies are directly relevant to remanufacturing practices for electric and electronic goods.	Maranesi and De Giovanni (2020) analysed firms' chances to consider circular economy and industrial symbiosis as a part of the corporate strategy	(Maranesi & De Giovanni, 2020)
		Marconi et al. (2018) defined an approach and a platform, dedicated to the WEEE sector, to favour the creation of industrial symbiosis opportunities	(Marconi et al., 2018)

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TABLE A1 (Continued)

Circular economy levels		Topic of the papers	References
		Feng et al. (2016) examined the role of the remanufacturing sector in a national economy as well as its symbiotic effects with other sectors for energy saving and emissions reduction	(Feng et al., 2016)
		Kobayashi et al. (2020) studied industrial symbiosis to propose a calculation of dynamic material flows in connected lifecycle systems	(Kobayashi et al., 2020)
	There is a variety of articles on different industrial sectors.	Hultberg and Pal (2021) explored the main strategic approaches to scale circular business models in the fashion retail value chain	(Hultberg & Pal, 2021)
		Zlamparet et al. (2017) evaluated the remanufacturing principles which can be adopted by entire the electronic manufacturing industry	(Zlamparet et al., 2017)
		Kanda et al. (2021) conducted a comparative case analysis of nine Swedish biogas companies and one branch organisation to demonstrate that adopting circular economy often requires companies to move from a firm-centric focus in their operational logic towards intensive interaction with an ecosystem of actors	(Kanda et al., 2021)
		Tapaninaho and Heikkinen (2022) examined the value creation in CE business from a stakeholder relationship perspective by conducting a case study of a Finnish energy company	(Tapaninaho & Heikkinen, 2022)
		Alblooshi et al. (2022) deployed an analytic hierarchy process approach to evaluate and prioritise alternatives for e-waste processing systems in the United Arab Emirates context	(Alblooshi et al., 2022)
MACRO LEVEL	At the macro level, there are heterogeneous studies spanning different geographic dimensions. None of these studies explicitly model a regional remanufacturing system for large electronic home appliances, but there is growing evidence that the regional dimension presents an appropriate scale for implementing circular business models applied to the white goods industry.	Scarpellini et al. (2019) analysed the impact and contribution of the circular economy to the debate about regional environmental management from the different perspectives of civil society, public administrations, and the private sector through a qualitative case study of the Spanish region of Aragon	(Scarpellini et al., 2019)
		Sigüenza et al. (2021) applied a dynamic life cycle assessment modelling framework to study the material use and climate impacts of the potentially large-scale adoption of two circular business models in the Dutch market of washing machines by 2050, considering the energy transition of the Dutch, European, and global regions	(Sigüenza et al., 2021)
		Talens Peiró et al. (2022) examined the reuse of washing machines at a local workshop in Barcelona with the objective of understanding the internal procedures for repair and reuse and defining	(Talens Peiró et al., 2022)

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TABLE A1 (Continued)

Circular economy levels	Topic of the papers	References
	indicators suitable to monitor these activities	
	Bahers and Kim (2018) studied the implementation of extended producer responsibility in the Midi-Pyrénées Region and the Toulouse's urban area by examining operational activities of regional and urban WEEE flows	(Bahers & Kim, 2018)
	Low and Ng (2018) proposed a methodological framework for flexible design of remanufacturing systems and demonstrate its application using a case study based on remanufacturing laptop computers for the Cambodian market	(Low & Ng, 2018)

APPENDIX B: DEMOGRAPHIC OVERVIEW OF THE PIEDMONT REGION

TABLE B1 Demographic overview of the Piedmont region. *Source*: https://ec.europa.eu/eurostat/

Province	Population	Households	Area (km^2)	Density (ab/km^2)	N. Of municipalities
Turin	2,208,370	1,047,234	6826.91	323	312
Alessandria	407,264	195,382	3558.78	114	187
Asti	208,286	95,158	1510.17	138	117
Biella	170,027	80,452	913.27	186	74
Cuneo	580,155	257,323	6894.83	84	247
Novara	361,916	162,794	1340.25	270	87
Verbano-Cusio-Ossola	154,249	73,702	2260.89	68	74
Vercelli	166,083	77,272	2081.60	80	82
Total	4,274,945	1,989,317	25,386.70	168.4	1180

APPENDIX C: ITALIAN LEGISLATION FOR THE WEEE MANAGEMENT

The *Legislative Decree 49/2014* arises from the transposition of *Directive 2012/19/EU*. Related to the Decree there are some Ministerial Decrees which define its implementation aspects. The most significant ones for Producers are the followings:

The Financial guarantees Decree—Ministerial Decree No. 68 of 9 March 2017 regulates the ways in which EEE Producers must provide the financial guarantees, applicable only for WEEE from private households.

The Rates Decree—Ministerial Decree of 17 June 2016 establishes the charges and payment methods for covering the operating costs deriving from the waste management system for electrical and electronic equipment.

The 'One-for-Zero' Decree—Ministerial Decree No. 121 of 31 May 2016 regulates the simplified procedures for the take-back by Distributors of small sized WEEE from households, free of charge and without the obligation to purchase an equivalent product.

The 'One-for-One' Decree—Ministerial Decree 65/2010 ensures the free take-back of the old equipment when purchasing an equivalent product.

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APPENDIX D: QUANTITY (IN KG) OF R2—LARGE HOUSEHOLD APPLIANCES COLLECTED BY (WEEE) COLLECTION CENTRES IN PIEDMONT IN 2022

TABLE D1: Data on R2—Large household appliances in the Piedmont region (2022). Legend: CdR: municipal collection centres; LdR: retailers collection centres; CrP: private collection centres; Inst: Installers. *Source*: www.raeeitalia.it

	R2 collected during 2022 (kg)		Collection centres (province)				
Piedmont region	Province	Municipality	CdR	LdR	CrP	Inst	Total
Turin	4,070,325	2,063,780	99	9	-	16	124
Alessandria	743,590	150,620	25	5	1	1	32
Asti	231,270	89,350	14	3	-	1	18
Biella	134,320	82,980	7	1	-	1	9
Cuneo	1,045,798	55,000	65	12	-	3	80
Novara	740,277	167,330	53	9	-	2	64
Verbano-Cusio-Ossola	440,160	148,990	22	-	-	1	23
Vercelli	265,800	171,210	12	2	-	-	14
Total	*7,671,540*						*364*

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APPENDIX E: DETAILED MAP OF THE COLLECTION CENTRES IN PIEDMONT REGION (FIGURE E1) AND AROUND THE MUNICIPALITY OF TURIN (FIGURE E2)

The centres specialised in the collection of WEEE are scattered around the regional territory, with a higher concentration near larger urban centres.

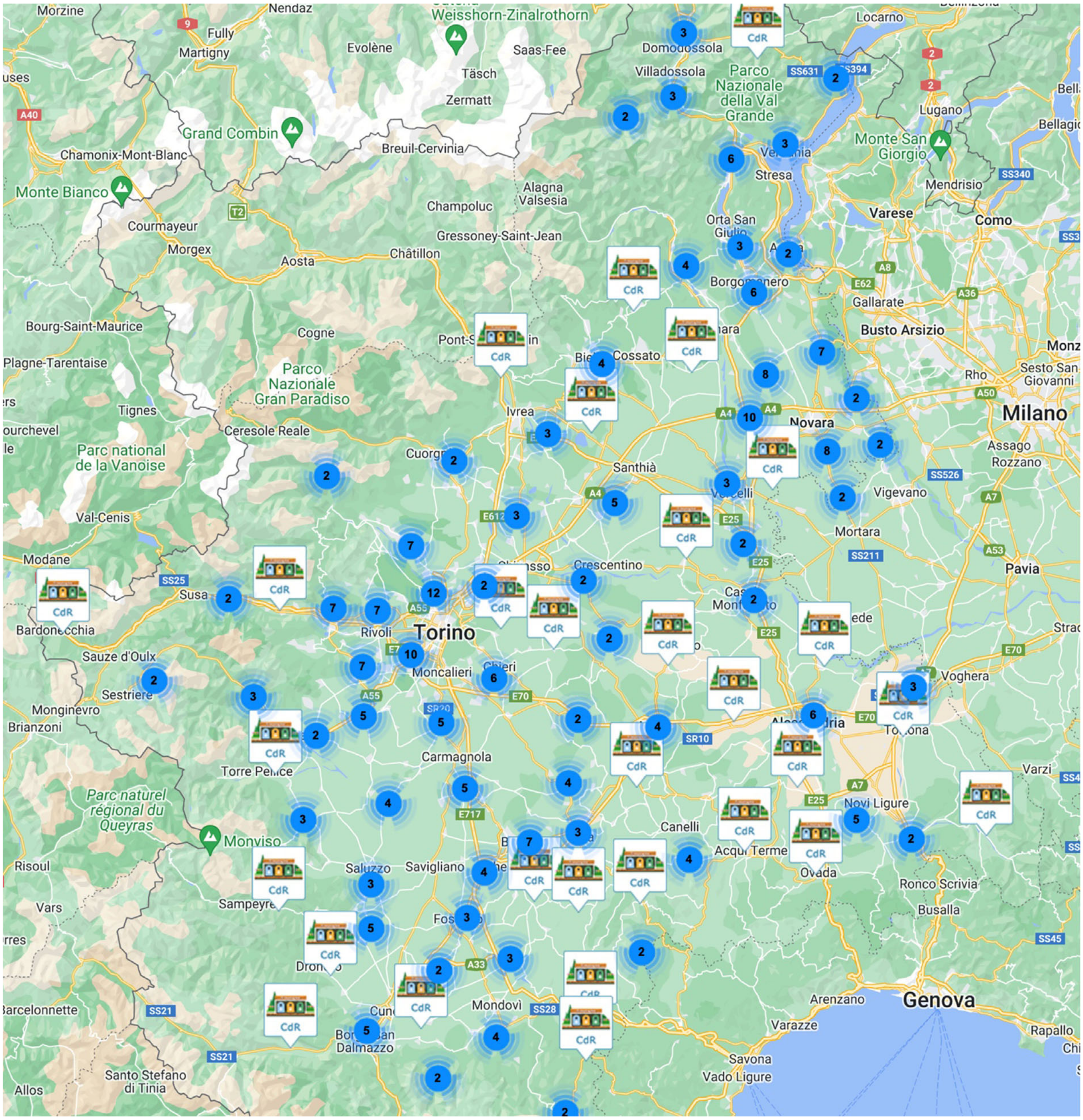

FIGURE E1 Territorial distribution of waste collection centres around the Piedmont region. *Source*: www.cdcraee.it

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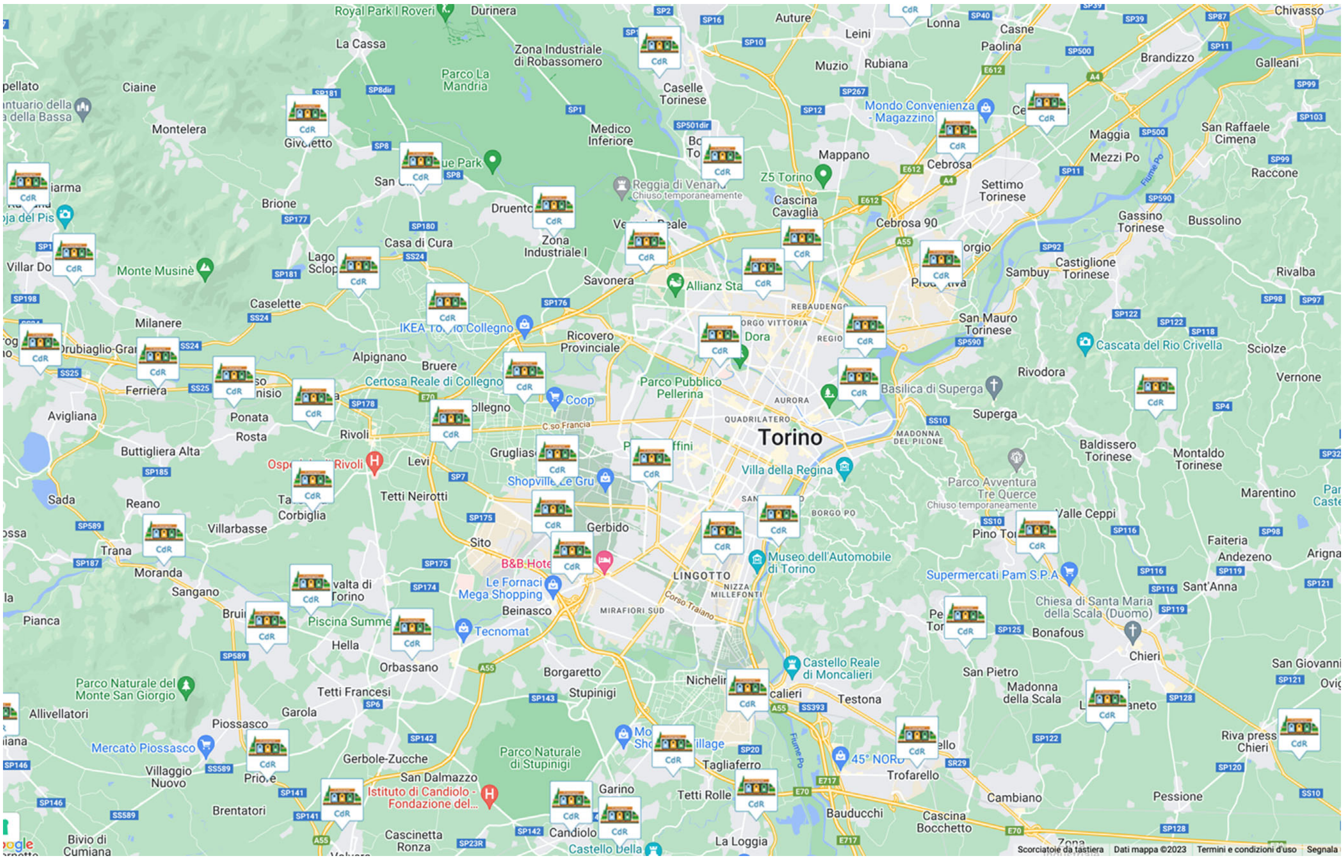

FIGURE E2 Territorial distribution of waste collection centres around the municipality of Turin. *Source*: www.cdcraee.it

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APPENDIX F: STAKEHOLDERS IN THE RECYCLING CHAIN FOR HOUSEHOLD WEEE

TABLE F1 Roles and responsibilities of stakeholders in the recycling chain for household WEEE. Source: adapted from (Magaliniet al., 2012).

Stakeholder	Roles and responsibilities
Producers	Join a compliance scheme for management of historical household WEEE (put on market before 31/12/2010, according to national transposition). May join a compliance scheme for new WEEE
Compliance schemes	Pick up WEEE in all collection points assigned by CdC RAEE. Deliver WEEE for treatment only to those treatment facilities accredited by the CdC RAEE. Each month, report to the CdC RAEE quantities collected.
Clearinghouse (CdC RAEE)	Ensures level playing field for all compliance schemes and uniform service levels for all collection centres enrolled in the system.Annually, assigns to compliance schemes collection points for WEEE pick-up, ensuring alignment with their market share. Monitors the quantities of WEEE collected by collection systems.
Consumers (waste holders)	Hand over WEEE to municipal collection points or retailers.
Municipal collection centres	Collect WEEE from citizens and/or retailers, divide it into five waste streams (R1–R5) and transfer it to compliance schemes for transportation to treatment plants.
Retailers	Collect WEEE from consumers (e.g. through old-for-new mechanism) and transport it to a municipal collection Centre (or consolidate it in so-called LdR) for subsequent pick up by compliance schemes.
Treatment plants	Carry out treatment of WEEE handed over by compliance schemes in accordance with minimum requirements set out in agreement between CdC RAEE and Recyclers' associations.

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APPENDIX G: DATA COLLECTION

TABLE G1 Overview of the interviews.

Interviewees	N. of interviews	Total duration of interviews (hours)	Period for data collection
Managing director (Astelav)	7	12.5	2019: January, April, September 2021: January, April 2022: October 2023: October
Managing director (Astelav & Ri-generation)	6	11	2019: January, April, 2021: January, April 2022: October 2023: September
Warehouse general manager	4	6	2019: March 2021: October 2022: September 2023: October
Warehouse director	4	6	2019: June 2021: June 2022: September 2023: June
Registry office manager	3	5	2019: February 2021: April 2023: June
Sales manager	3	5	2019: April, 2021: January 2023: September
Logistics director	3	4.5	2019: September 2021: October 2023: October
Operations manager	3	4	2019: January 2022: January 2023: September
Human resources manager	3	4	2019: May 2022: June 2023: September
Total	36 interviews	58 h	

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TABLE G2 Data sources.

Description of the data source and year	Number of pages
Secondary data	
Publicly available information	
Reports from previous research projects funded by public organizations	180
Archival documents	72
Company reports	37
Publications on industry's magazines	25
Press conferences and public speeches	15
Internal documents	
Other technical documents and material provided by the informants	170
Financial statements (2016 to 2023)	43
Company audit	11
Primary data	
Transcripts from direct interviews (2019 to 2023)	287
Total number of sources of evidence	840

APPENDIX H: ASSESSMENT OF THE CIRCULARITY OF THE REMANUFACTURED PRODUCT

In order to ascertain the circularity of the product, an assessment was performed on the energy consumption during the product's operation. It assumed that the washing machine reconditioned by Astelav was a Class A+ with a load capacity of 9 kg, and that the user, as an alternative to the purchase of a 'used' appliance, would have bought a new Class A+++ with the same load capacity. The annual energy consumption (as indicated by the energy label) of the class A+ washing machine is about 275 kWh, while that of the class A+++ is about 217 kWh per year, with a saving of around 21%. By converting energy consumption into resources and multiplying them by the 5 years of useful life of the reconditioned product, there is a difference in resources consumed by class A and Class A+++ of about 37 kg of fuel, equal to 0.05% of the resources saved, in terms of the materials used for producing the washing machine (Enel, 2017).

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