EDUCATIONAL MANUAL FOR PRACTITIONERS CAPACITY BUILDING FOR REMANUFACTURING IN PAAS IN PRODUCT-AS-A-SERVICE (PAAS)

DELIVERABLES 5.6 – SCANDERE PROJECT

Scaling up a circular economy business model by new design, leaner remanufacturing, and automated material recycling technologies

Project partners

Poznan University of Technology · KU Leuven · Elektro Recykling · Ecotic · Linköping University · compliance & risks · Grenoble INP UGA · B/S/H/ · ERA-MIN 3 · NCBR Narodowe Centrum Badań i Rozwoju

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The report was completed in April 2025.

DISCLAIMER

The content of this report reflects solely the opinions of the SCANDERE research team from Poznan University of Technology.

This project is supported by the EU co-funded ERA-MIN3 program under the grant number 101003575. Linköping University is financially supported by VINNOVA, Sweden's Innovation Agency (No. 2022-00070). Poznan University of Technology and Elektrorecykling S.A. are financially supported by NCBR, National Centre for Research and Development, Poland (No. ERA-MIN3/1/SCANDERE/4/2022). University Grenoble Alpes is financially supported by the French ADEME (Ecologic Transition Agency) under contract number 2202D0103. KU Leuven is financially supported by Fonds Wetenschappelijk Onderzoek (FWO) – Vlaanderen / Research Foundation – Flanders (project G0G6121N). Compliance and Risks is financially supported by Geological Survey Ireland (2021-ERAMIN3-001).

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EXECUTIVE SUMMARY

Remanufacturing restores used products to like-new condition, playing a key role in retaining product value within circular business models. Product as a Service (PaaS) is an example of a servitised business model that enables companies to generate value by actively managing the entire lifecycle of their products. Currently, the integration of remanufacturing within PaaS remains a niche practice, particularly for electrical and electronic equipment (EEE) in consumer markets.

This document introduces a new capacity building framework, Rem-Cap-Up, designed to help companies expand remanufacturing within PaaS models for B2C EEE markets. The framework addresses both the individual and organisational levels. At the individual level, it identifies the critical skills required for remanufacturing. At the organisational level, it outlines the prerequisites for implementing a PaaS model, designing efficient processes, and ensuring the availability of necessary resources to support a cost-effective and environmentally sustainable ("lean and green") remanufacturing approach. In addition, the framework emphasizes the importance of conserving critical raw materials.

The research methodology includes a literature review, a longitudinal case study, semi-structured interviews with experts, gap analysis, process mapping, and direct observation. These methods support the establishment of a viable remanufacturing process and the identification of essential organisational capabilities. The study addresses three key areas for capacity building in PaaS:

- Key challenges are enablers of implementing remanufacturing for EEE within PaaS models
- Identification of key capabilities that are required to overcome the challenges and activate enablers
- Guidance for companies to assess the existing capacities, measure the capacity gap, and support the development of missing capacities.

The findings provide actionable guidance for companies seeking to implement and scale up remanufacturing practices within PaaS circular business models.

1. INTRODUCTION - CRITICAL RAW MATERIAL AND THE POTENTIAL OF EEE SECTOR TO RECOVER THEM

The Circular Economy Action Plan (CEAP) of the European Union (EU) (COM/2020/98 final) identified the electronics and electrical equipment (EEE) sector as one of the sectors with the highest potential for circularity. At the same time, the dominant industry practice for waste electronics and electrical equipment (WEEE) is recycling. A change is needed to reduce reliance on recycling, which is not the most optimal solution for resource efficiency and sustainability (Howard et al., 2022). In order to unlock the circularity potential of the EEE sector, several actions are required, such as improving the durability, reusability, upgradability, and reparability of the product (Bressanelli et al., 2020; Cole et al., 2019). Furthermore, the broader implementation of value retention processes (VRPs) in particular remanufacturing is needed (Russell & Nasr, 2023).

Electrical and electronic equipment is one of the fastest growing waste streams in the EU. In 2019, 12 Mt of WEEE was generated in the EU compared to 11.6 Mt + in 2014. In 2022, 11.2 kg of electrical and electronic equipment waste were collected per inhabitant in the EU (Eurostat, 2024).The increasing volume of the disposal of fully or partially functional products because they could not be repaired, batteries could not be replaced, software could not be supported, or materials contained in devices could not be recovered. From the perspective of Circular Economy, the questions have risen about the possibilities of urban mining (Ottoni et al., 2020) and the increased application of various reuse scenarios for the electronical and electric equipment (EEE).

Critical Raw Materials (CRMs) are raw materials that hold significant economic and strategic importance for the European economy, yet their supply is associated with a high level of risk. These materials play a vital role in a wide range of sectors, including environmental technologies, consumer electronics, healthcare, steel production, defence, space exploration, and aviation. They are essential not only for the functioning of key industrial sectors and the development of future technologies but also for ensuring the long-term sustainability and resilience of the European economy (CRM Aalliance).

It is important to note that these materials are not considered 'critical' due to their scarcity alone. Rather, their classification as critical stems from a combination of three main factors. First, they have substantial economic importance for several strategic sectors within the European economy, such as automotive, aerospace, defence, healthcare, and environmental technologies. Second, they are subject to a high supply risk due to Europe's heavy dependence on imports and the concentration of production in a limited number of countries. Finally, there is a lack of viable substitutes for many of these materials, as they possess unique and reliable properties that are difficult to replicate and are essential for both current and emerging applications.

Within the EEE sector, household appliances present a significant market share in terms of volume, making them interesting use cases for analysis. For example, washing machines include a number of critical raw materials (CRMs). Critical raw materials such as neodymium, cobalt, tantalum, lithium, gold and silver are essential for producing components for household appliances, including motors, electronic systems and displays. However, the scarcity of CRMs and the environmental and social consequences of their extraction pose major sustainability challenges. The situation is further complicated by geopolitical factors, with China dominating the rare earth market and the Democratic Republic of Congo controlling much of the global cobalt supply. These dependencies expose manufacturers to substantial supply chain risks.

The availability of raw materials essential for the production of modern technologies, including household appliances such as washing machines, plays a significant role. However, these raw materials are geographically concentrated in a few countries (Fig. 1), which exposes global supply chains to various risks.

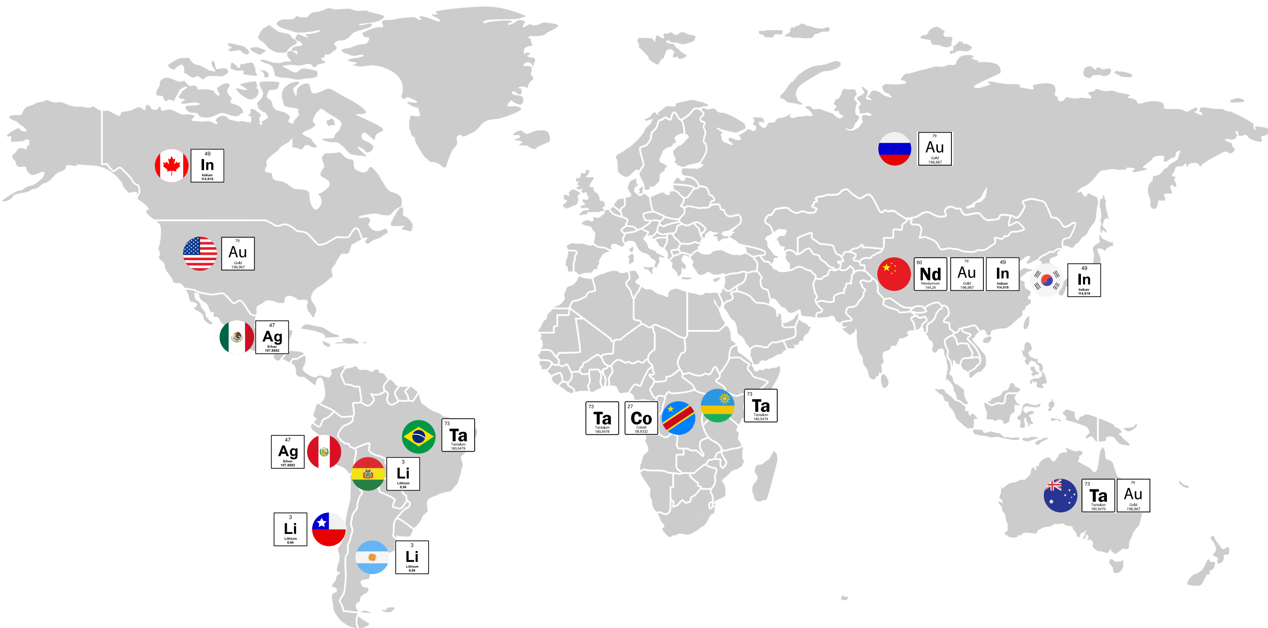


Figure 1. Global sources of critical materials

To verify the data obtained from literature and industry sources in the context of the Scandere project, multiple microscopic analyses were carried out to confirm the presence and distribution of critical raw materials within selected washing machine components, and to provide a more precise characterisation of their material composition. The investigation focused on a section of the control panel, where the chemical composition and distribution of elements were examined using scanning electron microscopy (SEM).

The primary objectives of the analysis were to assess the potential scope of remanufacturing, identify the presence and concentration of critical elements, and evaluate the feasibility of their recovery within the framework of the circular economy. The microscopic evaluation was conducted using a Tescan Mira 3 scanning electron microscope, while the chemical composition analysis was performed with an EDS ULTIM MAX 65 X-ray microanalyzer from Oxford Instruments, operated with AZtec software. The accelerating voltage was set to 12 kV. All analyses were conducted at the Faculty of Materials Engineering and Technical Physics, Poznan University of Technology.

Figures 2–3 present an example of the chemical composition analysis of a selected part of the internal computer of the washing machine. The microscopic image was taken using a BSE detector, while the chemical composition of the selected area was identified using an EDS detector. Table 1 shows the results obtained from the chemical composition.

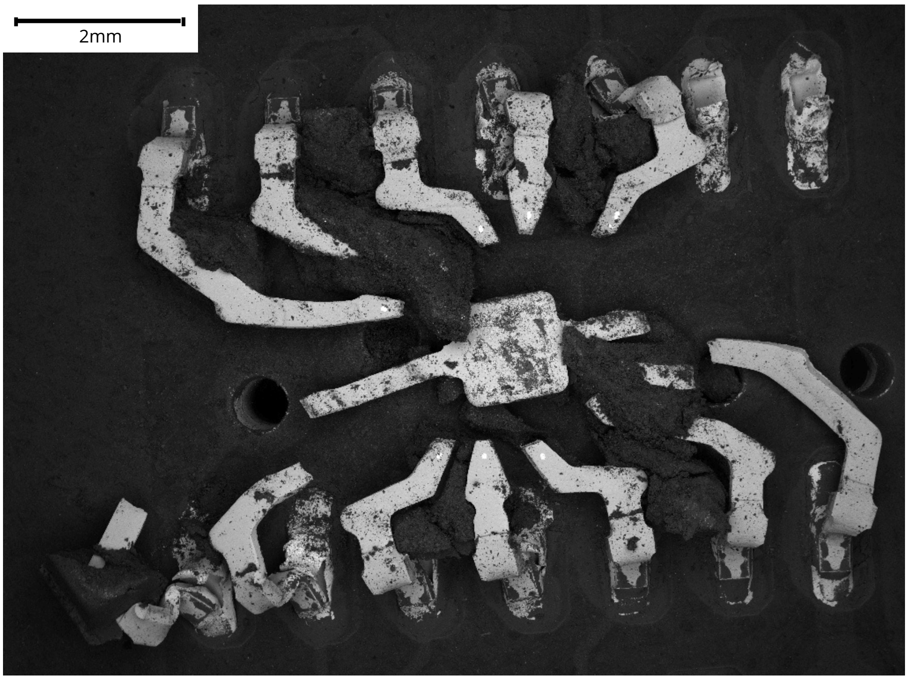


Figure 2. The interior of the controller integrated circuit

Figure 3. Distribution of elements on the surface of an integrated circuit

Table 1. Chemical composition of the internal computer sample

Chemical composition [wt.%]							
C	O	Ni	Sn	Si	Ba	Pd	Au
42,7	22,8	13,6	5,7	5,6	2,2	1,6	1,4

On the basis of the analysis of the elemental distribution on the surface of the examined area, the presence of elements such as gold (Au), silver (Ag), palladium (Pd), nickel (Ni), tin (Sn), and antimony (Sb) was identified. Gold and silver, marked in their respective colours, are primarily located in the areas of conductive paths, indicating their key role in ensuring electrical conductivity and corrosion resistance. Palladium and nickel are concentrated at contact points, which require durability and mechanical stability. The distribution of tin suggests its presence in solder joints connecting circuit components, while antimony appears in small amounts, likely as an alloying element or an additive in solder.

In addition, the results of the SEM analysis can confirm the information available in the literature sources. The presence of elements such as gold (Au), silver (Ag), and palladium (Pd) on the surface of the analysed components is in accordance with the data contained in the literature and summarised in Table 1, particularly in electronic modules such as the internal control computer and control panel. The detection of additional elements, such as nickel (Ni), tin (Sn), and antimony (Sb), further confirms the designation of further development of remanufacturing strategies as well as raw material recovery, especially for components with complex material composition.

Therefore, reducing reliance on CRMs is a strategic priority. While recycling plays a vital role in easing pressure on primary resources, current levels of CRM recovery from household appliances are insufficient and require significant improvement. Microscopic analysis conducted in this study has confirmed the widespread presence of critical elements in various washing machine components, including the internal computer, temperature sensor, electrical system, structural parts, and functional elements such as the heating system and door hinge.This highlights the potential for greater recovery of valuable materials if more advanced recycling processes are adopted.

To address these challenges and support a more sustainable trajectory, the household appliance industry must explore alternative ways to recover critical raw materials (CRMs) and transform existing practices to extend product life cycles and durability through repair, refurbishment and remanufacturing, supported by circular business models.

The introduction of a cascading model, where recycling is considered a last resort, is essential. At the same time, there is a need to develop innovative recycling technologies that can recover CRMs more efficiently. This includes improvements in separation techniques and the establishment of industrial-scale recycling infrastructure. In addition, research into alternative materials that could replace CRMs in key components should be intensified. Efforts should target substitutes for rare earth elements, cobalt, tantalum, and indium, with collaboration between industry, academia, and policymakers being vital to accelerate innovation.

In parallel, a shift toward circular product design is needed. Appliances must be designed with longer lifespans, ease of disassembly, and greater energy efficiency in mind. Optimising production processes to reduce material waste will contribute to decreasing the use of virgin resources. By embedding circular economy principles throughout the value chain, the household appliance sector can significantly mitigate its environmental impact and reduce dependence on non-renewable inputs.

Finally, diversification of raw material sources—through local resource development and strategic international partnerships—can enhance supply chain resilience. The ability of the household appliance industry to adapt flexibly to the CRM challenge, supported by coordinated investments in recycling, material innovation, and resource management, is key to ensuring long-term sustainability in the face of climate change and mounting environmental pressures.

2. PAAS AND REMANUFACTURING AS ENABLERS OF CIRCULAR ECONOMY AND RECOVERY OF CRM IN EEE CONSUMER GOODS

2.1. PAAS CHARACTERISTICS AND BUSINESS MODEL DEVELOPMENT

Servitisation influences companies' business models, as it involves moving from selling physical products to generating revenue streams through offering access to the usage of product or its performance, or functions (Adrodegari et al., 2017). The concept of product service systems is relatively well established in the literature. Product-service-system (PSS) is defined here as 'mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs' (Tukker & Tischner, 2006). The servitisation approaches can be classified as (Tukker, 2015):

- product-oriented;
- use oriented (e.g., product renting, sharing, and pooling) intensify the use of the products;
- result oriented.

Product-service systems (PSS) are business models in which the product manufacturer usually ofers services in addition to selling the products, or even takes over the operation of the products instead of selling them (Blüher et al., 2020).

Product-as-a-Service is a special case of product-service system, where a customer is not the owner of the product. The ownership of a product is retained by another party in the supply chain (most likely by retailer or producer).

Original equipment manufacturers (OEMs) when offering PaaS take higher responsibility for product performances in the use phase than those selling products (Sakao & Nordholm, 2021)

PaaS is classified as a subcategory of Product-Service Systems (PSS) (Brissaud et al., 2022) and is increasingly recognised as a promising model for improving resource efficiency while optimising the use of critical raw materials (CRM) (Sakao et al., 2023).

PaaS characteristics:

- OEM/Retailer retain the product's ownership when providing end users with offerings (products & services).
- End users obtain access to the product functions in subscription contracts (i.e., flat rate payment per defined time period, pay-per-use, etc.)
- Cost of installation & delivery is part of an offer
- Repair and servicing are included and usually covered by PaaS provider
- New, as well as refurbished/repaired/remanufactured products are offered
- Dedicated apps/IoT to monitor the life cycle of product & use patterns are installed.

Potential benefits for OEMs from providing PaaS:

- It can improve resource-efficiency though extended time of use of products (additional or extended income streams)
- It allows to control the product through whole life cycle
- It allows to recover the Critical Raw Materials (e.g., 40% of CRM recovery more than in linear models)
- It helps to increase the recovery rate to meet the legal requirements (improved rates in recycling, improved remanufacturing rates, e.g.)
- It allows to dynamically manage the usage phase of product
- It provides information feedback to improve the design of products and their durability.

In PaaS circular business model, the ownership of cores remains with the original equipment manufacturer (OEM) or PaaS provider. That allows for proactive management of contract duration to maximise product value and potentially minimise remanufacturing costs (Golinska-Dawson et al., 2024). This reduction in costs is mainly attributed to the improved core quality thanks to controlled product usage and maintenance. Furthermore, the integration of digital technologies and life cycle data analytics enables OEMs to gain real-time insights into the health and condition of products (referred to as core quality) (Sakao & Nordholm, 2021).

Potential Benefits for Customers from Participating in Product-as-a-Service (PaaS):

- No need for initial investment
- Hassle-free usage phase, as repairs and servicing are the responsibility and cost of a PaaS provider
- Access to newer, more resource-efficient products (e.g. more energy- and water-efficient appliances)
- End-of-use product management is handled by a PaaS provider.

In the case of electrical and electronic products for consumer markets, pilot projects have been carried out to explore Product-as-a-Service (PaaS) options involving remanufacturing (Bressanelli et al., 2020). In practice, however, servitisation in the electrical and electronic equipment (EEE) sector remains immature. Most original equipment manufacturers (OEMs) generate only a small share of their turnover from services, which are primarily limited to traditional product-related offerings such as spare parts, technical assistance, and maintenance (Adrodegari et al., 2017).

The circular business model shall (Golinska-Dawson, 2020):

- provide the value for stakeholders by delivering products and or services;
- create cooperation both on downstream and upstream in the supply chain;
- capture value and sustain the financial viability and environmental sustainability;
- maintain financial stability.

Fig. 4. presents the generic PaaS model with enforced circularity due to the value retention processes.

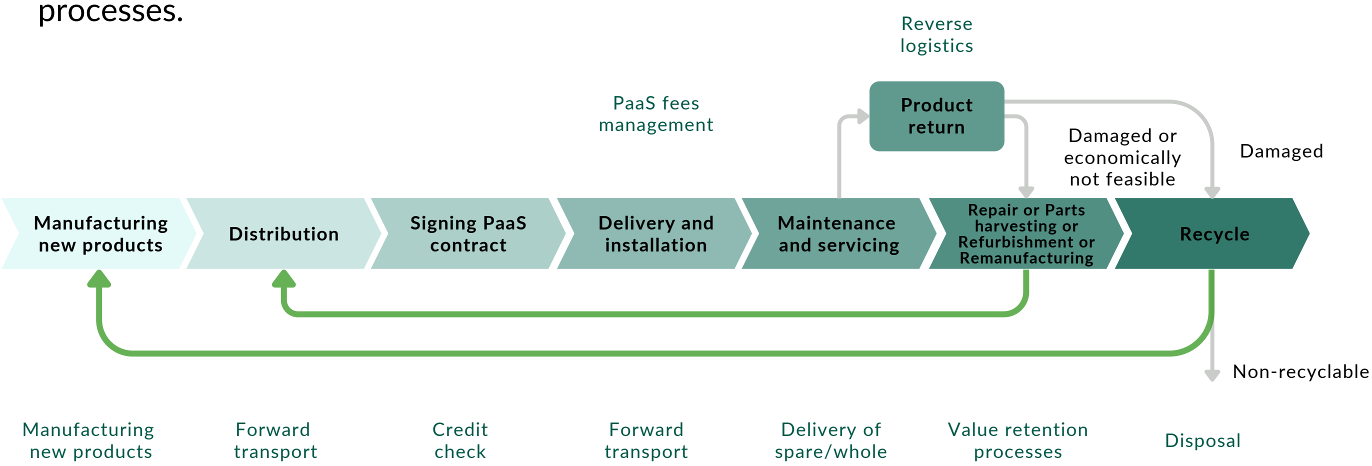


Figure 4. Example of PaaS with circularity based on (van Loon i van Wassenhove 2020)

RISKS OF IMPLEMENTING PAAS

Despite many benefits the introduction of PaaS might results also in negative effects such as overconsumption, due to lack of the initial purchase cost or careless use of products by consumers (due to "not my property" attitude). PaaS models are designed to support circular economy practices such as remanufacturing, refurbishing, and recycling. However, the effectiveness of these practices can be compromised if users do not handle the products responsibly, leading to increased wear and tear and reduced product lifespan (Golinska-Dawson, Zysnarska &Pender 2024).

The shift from traditional product sales (linear business models) to offering Product-as-a-Service (PaaS) within circular business models fundamentally alters the economic and organisational conditions for companies. In a conventional sales model, manufacturing and distribution costs are recovered directly through the purchase price, with additional revenue generated from repair services after the warranty period ends. In contrast, circular business models enable economic value to be captured over multiple product life cycles and through improved resource efficiency. However, revenue and cost streams are distributed differently, often unevenly, across these extended and repeated life cycles.

2.2. CIRCULAR PRACTICES IN EEE

In the EEE sector, the circularity is supported by legislative document:

- WEEE Directive (2012/19/EU) of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (recast from WEEE Directive 2002/96/EC), that regulates the collection, treatment, and recycling of EEE waste, and encourages product designs that facilitate disassembly and recovery of materials.
- Ecodesign for Sustainable Products Regulation (ESPR) – Regulation (EU) 2024/1781 of the European Parliament and of the Council of 18 July 2024, that updates the framework for the setting of Eco-design, and introduces mandatory sustainability requirements on durability, reparability, recyclability, and environmental performance, including Digital Product Passports to provide detailed information for consumers, recyclers, and repairers.
- Restriction of Hazardous Substances (RoHS) Directive (2011/65/EU), that restiricts the use of ten hazardous substances in EEE that can be substituted by safer alternatives, including: lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), bis(2-ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), dibutyl phthalate (DBP) and diisobutyl phthalate (DIBP).
- Right to Repair Directive (2024/1799) of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods. Its main objective is to promote more sustainable consumption by increasing the repair and reuse of goods, both during and after the legal guarantee period. The directive supports the European Green Deal and is part of a broader legislative effort to extend the lifespan of consumer products. It complements other initiatives, such as the Ecodesign for Sustainable Products Regulation (which replaces the Ecodesign Directive) by promoting reparability through product design and spare parts availability. It also works alongside Directive (EU) 2024/825 on Empowering Consumers in the Green Transition, which enhances consumer access to information on product durability and reparability at the point of sale.

Electrical and electronic equipment (EEE) sector implements various practices to move from wasteful linear business models to cascading and resource efficient solutions along EEE supply chain. Value-retention processes (VRPs), allows to extend the expected service life, and to activate full potential of recapturing resource value (materials, structural form, work load, energy and functions) embedded in products beyond the recycling of materials (Russel and Nasr, 2020).The value retention processes are crucial part of cascading the materials flows in Circular Economy, and they are the entry point for further recycling of products, which are not feasible any more for VRPs. The CE approach in the EEE sector is shown in Fig. 5.

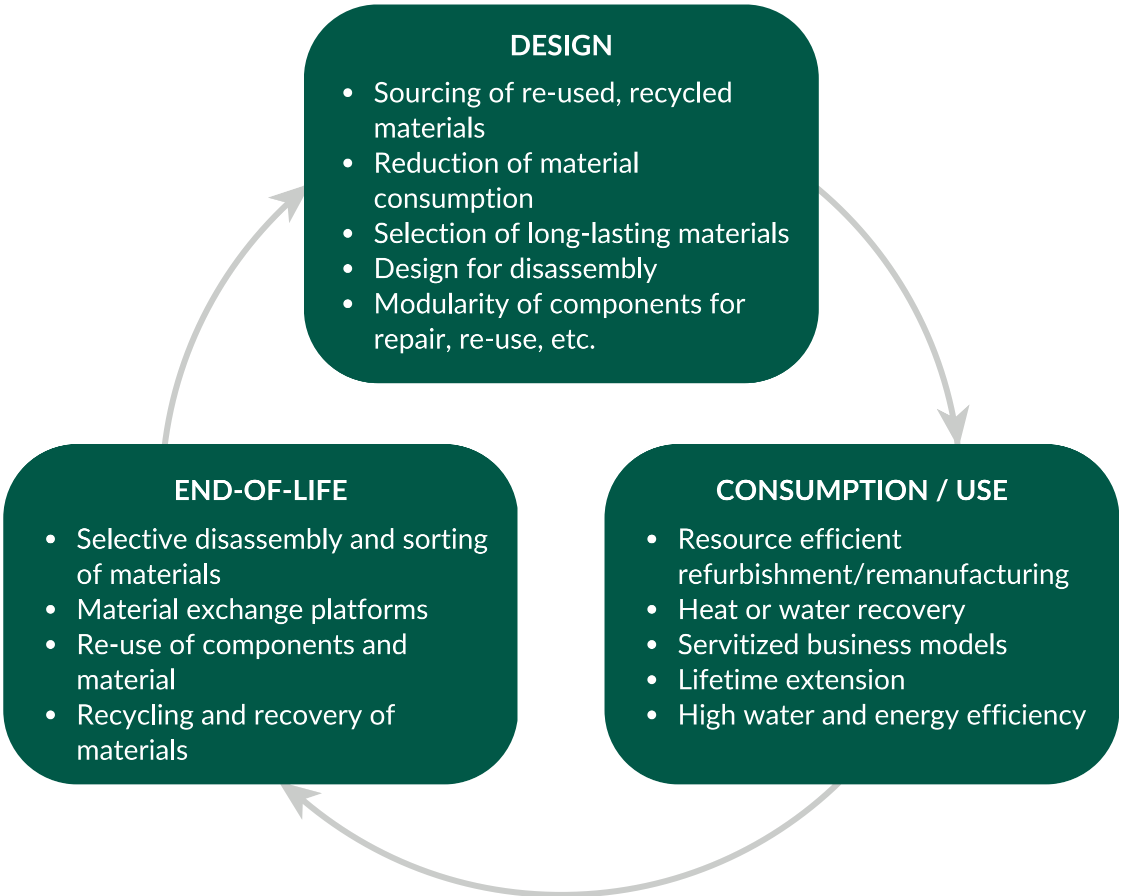


Figure 5. Circularity in EEE

According to the International Resource Panel (IRP, 2018), value-retention services can be categorised as follows:

- Full-Service Life Processes – These aim to provide a completely new life for the product during each usage cycle and are typically carried out in industrial settings.
- Partial-Service Life Processes – These focus on completing or slightly extending the expected service life of the product.

The most popular value retention processes in the EEE sector include:

- Direct reuse (Partial Service-Life VRPs),
- Repair (Partial Service-Life VRPs),
- Refurbishment (Full-Service Life VRPs),
- Remanufacturing (Full-Service Life VRPs).

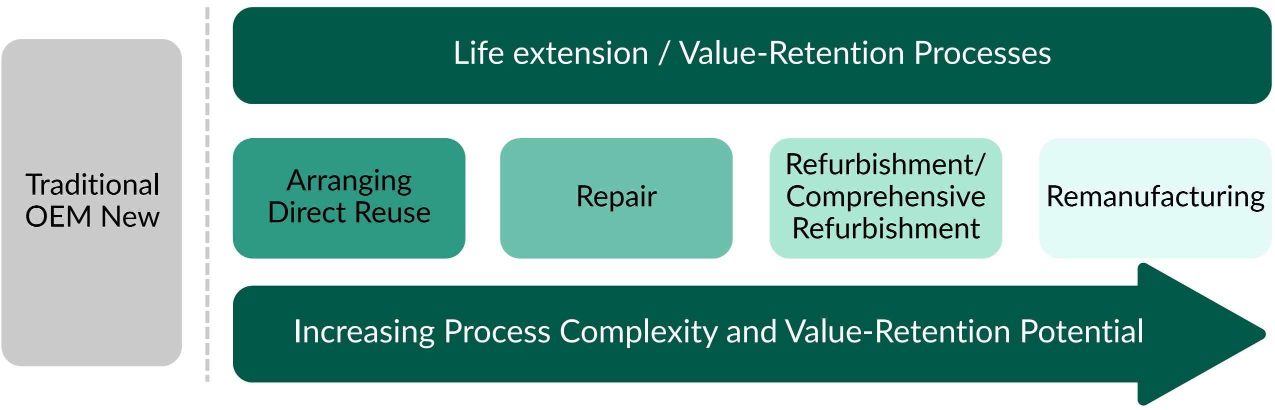


Figure 6. Definitions and structure of value-retention processes (Source : IRP 2018)

The definition and characteristics of the Value Retention Processes are provided in Table 2.

Table 2. Definition of Value Retention Processes (VRPs)

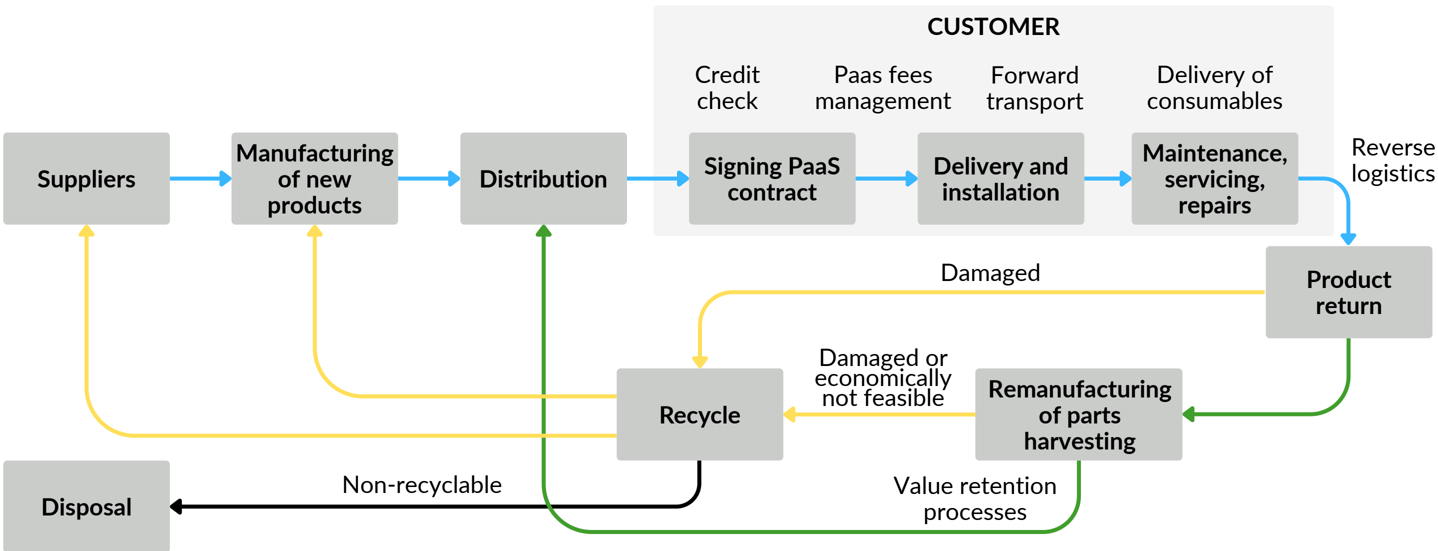
Name of VRP	Processes	Reason for End of Use (EoU)	End of useful service life	Output of VRP
Direct reuse (Partial Service-Life VRPs)	Collection, inspection and testing, cleaning, and redistribution to new users. No disassembly, removal of parts, or addition of parts	User requires an upgraded product, or no longer need the product, or change preferences	Prematurely, as not yet fulfilled its expected life	The product is functional but not guaranteed to meet original specifications.
Repair (Partial Service-Life VRPs)	Collection, inspection and testing, cleaning, some worn or damaged parts removed, and new parts added, redistribution (mainly to the original user)	Failure of defective component	Constrained to complete its original expected life if not repaired	After fixing of a specified malfunction, fully functional product for the duration of its expected life.
Refurbishment (Full-Service Life VRPs)	Collection, inspection and testing, cleaning, some worn or damaged parts removed, and new parts added, redistribution (mainly to the original user)	Failure of defective component	Constrained to complete its original expected life if not repaired	After fixing of a specified malfunction, fully functional product for the duration of its expected life.
Remanufacturing (Full-Service Life VRPs)	Collection, inspection, complete disassembly at the component-level or module-level of product in the industry settings, cleaning, testing replacing or recovering modules or components, upgrades, reassembly, final quality testing, redistribution to the original or s new user	Need to increase or restore performance or functionality for next service life cycle	To duplicate the expected service life	As good-as-new or better-than-new functionally for the duration of new service life with warranty

2.3. REMANUFACTURING

Remanufacturing is an industrial process whereby products, referred to as cores, are restored to 'like a new' condition. During this process, the core passes through a number of operations, e.g., inspection, disassembly, part reprocessing, reassembly, and testing, to ensure that they meet the desired quality standards (Östlin et al., 2008). It is different than refurbishment which allows to modify/update a used product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements. Refurbishment aims to provide a fully functional product to be used for the duration of its expected lifespan.

Remanufacturing enables original equipment manufacturers (OEMs) to cascade material flows and optimise product usage cycles within the framework of the circular economy (CE) (He et al., 2024). In the context of electrical and electronic equipment (EEE), VRPs contribute to extending the expected service life and recovering the embedded resource value by encompassing materials, products, labour, energy, and functions, beyond what is achievable through conventional material recycling (Neto et al., 2023). Remanufacturing plays a pivotal role in facilitating the circular economy, as it enables the restoration of used products to a condition comparable to new, thus extending product life cycles and minimising resource depletion (Goltsos et al., 2019).

The emergence of Product-as-a-Service (PaaS) represents a paradigm shift in remanufacturing, by redefining its operational boundaries and establishing a closed-loop supply system that significantly mitigates uncertainties related to core availability (Golinska-Dawson et al., 2024). PaaS facilitates more effective planning and management of remanufacturing operations, leading to a reduction in overall costs (van Loon & Van Wassenhove, 2020). Compared to traditional open-loop remanufacturing, which is often constrained by variability in core availability and quality, PaaS shall offer more favourable conditions to optimise remanufacturing efficiency. The example of a PaaS with remanufacturing is presented in Fig. 7.



Legend: Arrows represent flow of products/materials in the system: blue — new; green — with VRPs; yellow— recycled; black —disposed.

Figure 7: An example of a PaaS with remanufacturing

The remanufacturing process varies depending on the case and industry. Various parties in the supply chain can carry it out, including original equipment manufacturers (OEMs), original equipment suppliers (OESs), independent remanufacturers (IRs), and subcontractors/contracted remanufacturers (CRs). For this reason, various studies on generic remanufacturing process models can be found in the literature. One of the most frequently cited models is that of Sundin (2004), which identifies the following seven generic remanufacturing processes: inspection; cleaning; disassembly; reprocessing; reassembly; testing; and storage. Materials flowing through the remanufacturing process include used or discarded products ('cores'), new parts and components from cannibalised products. To initiate remanufacturing, the following steps should be considered:

1. To select a product family with regard to their potential for circularity.
2. To involve of actors which are crucial for remanufacturing,
3. To iteratively identify prerequisites and assess system performance, the prerequisites for EEE remanufacturing on the B2C market are reviewed, as presented in Table 3.
4. To develop industrial process of remanufacturing.
5. To refine and validate.

Table 3. Perquisite for the EEE remanufacturing on B2C – CoLAR analysis framework
Source: The CoLAR analysis framework is based on the perquisites identified by (Vogt Duberg et al., 2020)

Perquisite	Current implementation	Experts' assessment	Enforcing circularity in PaaS
Core availability & reverse logistics system	very low/low	Current collection for B2C is volume oriented, all the products are collected & transported together. There is no visual inspection or assessment of the technical state of EoU/EoL products (they become WEEE).	Need for building capacities and partnerships for EEE collection in a selective way with inspection & quality pre-assessment.
Labor skills & availability of staff	low	Remanufacturing is very labor-intensive. The required set of skills is much broader than in production of EEE. It takes 6-12 months to train an employee for EEE reman/refurbish. There is a shortage of employees for remanufacturing. The linear mindset of managers is a challenge.	Need for training of employee to develop the remanufacturing skills. The production workers in most cases don't have skills to commence reman. Need to extend the servicing network or to build partnership with independent remanufacturers.
Access to the market and activization of key actors	low/medium	The awareness of availability or reman products is low, thus demand is very low.There is lack of common understanding on what is a remanufacturing /refurbishment product. There is no industry recognized quality and safety standards for EEE on B2C. The willingness to pay for reman product is lower than for new products. It is difficult to achieve economy of scale and provide economic viability of EEE remanufacturing on B2C. There is high competition from cheap & low quality new EEEs.	Need for building the customers' awareness about PaaS and reman products. Building direct channels of communication with customers for PaaS offering. Need for new approach to administration of PaaS which secures the return of products at the end of PaaS contracts, and which protects from product misuse or extensive use.
Remanufacturing, process technology & equipment (machines, tools, devices and IT systems).	low/medium	The know-how on remanufacturing of EEE for B2C is very limited. Most OEMs are not involved in remanufacturing operations. The cost of the remanufacturing process due to low economy of scale is higher than manufacturing new product. The non-destructive disassembly of EEE is tricky, due to the linear product design.	Need for providing tools for the assessment of economic and environmental benefits for both OEM and customers. Need for resource - efficient reman process design (lean and green)

The results of the experts (10 interviews with a duration of 90-150 minutes) done in the framework of Scandere project have shown, that the improvement of the take-back system might be one of the main stimulators for development of remanufacturing in EEE sector. The experts have in particular risen to need for implementing solutions, such as:

- visual inspection of (W)EEE at the collection;
- sorting at the collection;
- W(EEE) collection points and multiple ways for consumers to dispose of (W)EEE should be further developed;
- distinguishing at the collection between EEE and WEEE, in order to avoid administrative burden related to WEEE;
- developing the remanufacturing and repair processes with usage-based or access-based models, such as PaaS, leasing, renting, subscriptions,
- sharing should be promoted among consumers.

The experts have also mentioned the need for developing new partnerships and subsidising the take-back system in order to make it more cost-efficient.

The development of an industrial remanufacturing for EEE is presented in Fig. 8.

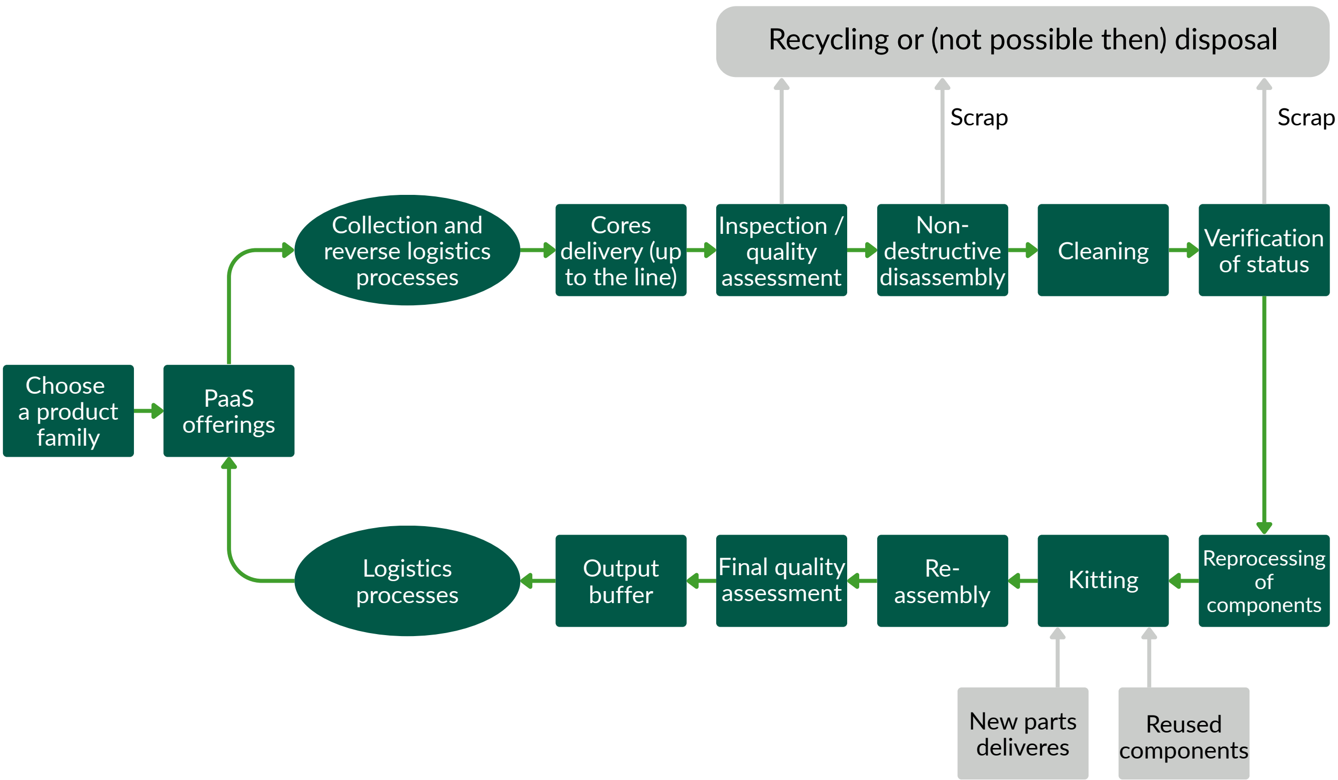


Figure 8 - Remanufacturing in PaaS (adopted from Golinska-Dawson et al. 2024)

3. CHALLENGES AND ENABLERS OF REMANUFACTURING IN PAAS

According to the previous report by International Resource Panel (IRP, 2018), the main obstacles to upscale the value recovery processes in the EEE sector result from:

- Regulatory barriers related to the availability and access to cores on EEE markets (for example restrictions on WEEE classification as e-waste, restriction on import-export of VRPs products).
- Collection system barriers, related to the configuration of WEE reverse logistics network with strong focus on the recycling processes, thus making VRPs difficult (for example: End-of-Use (EoU) still functional products mixed with WEEE and damaged during collection and transportation).
- Economic and technological barriers, such as the limited know-how on VRPs related technologies and skills, combined with the growing number of multiple models and generations of EEE, which make it difficult to build up capabilities for cost-efficient, and environmentally friendly operations (low economy of scale).
- Customer-related barriers, related to customer purchasing behaviors and preferences for new products, resulting in limited willingness-to-pay for VRPs products.
- Market-related barriers, such as lack of standards, certifications, and misinformation about refurbished or remanufactured products.

Through a systematic literature review, we extend the above classification framework by juxtaposing it with PaaS characteristics. The proposed categories of challenges and enablers are as follows (Golinska-Dawson et al., 2024):

RELATED TO THE PRODUCTS

RELATED TO THE POLICY AND LEGISLATION

RELATED TO THE CUSTOMERS AND MARKET

RELATED TO THE CHARACTERISTICS OF SERVITISED BUSINESS MODEL

RELATED TO THE PROCESS PERSPECTIVE

RELATED TO THE SUPPLY CHAIN AND REVERSE LOGISTICS

PRODUCT-RELATED

CHALLENGES

Most electrical and electronic equipment (EEE) is still designed for linear sales models, meaning that limited durability and suboptimal quality often hinder remanufacturing efforts (van Loon et al., 2022; van Loon & Van Wassenhove, 2018). In EEE markets, increasing product complexity and heterogeneity can be observed, along with a shift towards sleeker, more compact designs that incorporate proprietary fasteners and joints. A lack of design features to support disassembly and reassembly further complicates non-destructive dismantling processes, increasing the risk of damaging the product core (Sakao & Sundin, 2019; Russell & Nasr, 2019). Moreover, the rapid pace of technological innovation in the EEE sector can render remanufacturing economically unfeasible, as older products may be perceived as less attractive due to higher energy or water consumption (Khan et al., 2018).

ENABLERS

Establishing feedback loops that capture data from the product's usage phase can support user-centric design and enable the development of more durable, remanufacturable products (Brissaud et al. 2022; Arredondo-Soto et al. 2022). Insights into usage patterns can support redesign for enhanced modularity and ease of disassembly, as key drivers of effective remanufacturing (Reuter et al. 2018; Jensen et al. 2019). Smart sensors and Internet of Things (IoT) technologies are essential tools for collecting of real-time health data on products, allowing for early, proactive classification into optimal value-retention scenarios before products reach remanufacturing facilities (Subramoniam et al. 2021; Bressanelli et al. 2020)

POLICY AND LEGISLATION

CHALLENGES

Current EU WEEE (Waste Electrical and Electronic Equipment) regulations prioritize collection and recycling volume targets. This results in bulk collection systems with little to no pre-sorting, relying on destructive disassembly methods like shredding, followed by material sorting (Boldoczki et al. 2020; Coughlan & Fitzpatrick 2020). Since recovery rates are calculated at the aggregate level, many producers outsource reverse logistics to third parties (Parajuly & Wenzel 2017). Additionally, the lack of tax incentives and fears of double taxation hinder OEMs from transitioning to remanufacturing under PaaS models (Svensson-Hoglund et al. 2021; Bressanelli et al. 2019; Yang et al. 2019). The absence of standardised definitions and quality criteria for remanufactured EEE further complicates market acceptance (Svensson-Hoglund et al. 2021; Bressanelli et al. 2019).

ENABLERS

Recent policy shifts emphasising product durability and reparability support remanufacturing. Initiatives like France's Reparability Index encourage OEMs to reconsider product design for easier repair—an approach compatible with remanufacturing (Dalhammar et al. 2021). Eco-design regulations are also playing a growing role in promoting remanufacturability (Sakao & Sundin 2019; Jensen et al. 2019).

CUSTOMER AND MARKET-RELATED

CHALLENGES

Consumer awareness of remanufactured EEE remains low (Patwa et al. 2021; Gülserliler et al. 2022). Studies show that customer education is critical for the success and scalability of remanufacturing in PaaS (Zhou et al. 2021). However, consumer perceptions of remanufactured goods often associate them with inferior quality, leading to reduced willingness to pay full price compared to new products (van Loon et al. 2020; Kleber et al. 2018).

ENABLERS

PaaS can improve customer access by offering convenience and cost benefits. Typically, customers pay a regular subscription fee that covers servicing and maintenance, spreading the costs over time (Saccani et al., 2017; Kambanou & Sakao, 2020). Different customer segments may be attracted to various pricing and service models (e.g. pay-per-use or leasing new or remanufactured units) (Bressanelli et al. 2019b). The increasing awareness of environmental issues also supports consumer acceptance of remanufactured products (Vafadarnikjoo et al., 2018).

SERVITISED BUSINESS MODEL

CHALLENGES

Transitioning to a PaaS model involves new administrative burdens, including customer verification and contract management (van Loon et al. 2022). Cash flow is another concern. This A the upfront production and logistics costs are not immediately offset by the spread-out revenue from subscription payments. Furthermore, balancing costs between OEMs and customers under Total Cost of Ownership (TCO) models is complex. Manufacturers bear the cost of remanufacturing and repair. Effective fee structures require extensive data, which remains scarce in B2C EEE pilot programs (van Loon et al. 2022; van Loon & van Wassenhove 2018).

ENABLERS

PaaS provides OEMs with end-to-end control of product lifecycles, enabling them to optimise decisions relating to repair, remanufacturing or recycling (Jensen et al., 2019; Kjaer et al., 2018). Revenue streams can be increased through multiple customer contracts and the use of remanufactured parts for servicing (Pialot et al., 2017). PaaS also enables OEMs to bypass traditional retail channels and establish direct relationships with customers. IoT-enabled feedback loops provide continuous usage data to enhance remanufacturing planning and iterative process improvement (Vogt Duberg et al., 2021; Arredondo-Soto et al., 2022; Bocken et al., 2018).

PROCESS PERSPECTIVE (VALUE RETENTION PROCESS, VRP)

CHALLENGES

OEMs often lack experience in EEE remanufacturing, which is more labour-intensive and variable than conventional manufacturing. Workers need diverse technical skills, which are often lacking (Golińska-Dawson 2019; Kurilova-Palisaitiene 2021). Managerial mindsets focused on linear sales models and concerns over cannibalising new product sales also hinder progress (Widera & Seliger 2015; Yang et al. 2019). Without economies of scale, remanufacturing can be expensive—particularly during early transitions. Maximising product value retention requires proactive lifecycle management and timely collection (End-of-Use rather than End-of-Life) (van Loon et al. 2018, 2022).

ENABLERS

PaaS reduces uncertainty in remanufacturing by ensuring more predictable product returns (Opresnik & Taisch 2015). Reusing EEE across multiple contracts generates economic benefits (Krystofik & Gaustad 2018; Gülserliler et al. 2022). OEM-managed remanufacturing can boost resource efficiency by preserving embedded value (Morseletto 2020), extending product lifespans and reducing the need for replacements (Blomsma et al. 2019). Green branding and environmental goals further incentivise remanufacturing (Vogtlander et al. 2017).

SUPPLY CHAIN AND REVERSE LOGISTICS

CHALLENGES

Many original equipment manufacturers (OEMs) lack the expertise to implement efficient take-back systems. In Europe, nearly half of EEE waste is collected improperly, often ending up in household waste or informal recycling streams (Habib et al. 2022). PaaS-driven remanufacturing requires redesigned reverse logistics and strategic partnerships to enable cost-effective core assessment and sorting (Parajuly & Wenzel 2017; Prajapati et al. 2022). Current collection methods mix different brands and models, which makes sorting and remanufacturing logistically challenging and expensive (Anandh et al. 2021). Cross-border transport regulations on used EEE further limit scalability, often necessitating small, decentralised operations (Svensson-Hoglund et al. 2021).

ENABLERS

An effective PaaS system relies on timely product returns in good condition to reduce remanufacturing costs and scale operations. Government subsidies can support early-stage development of dedicated take-back systems and value chain collaboration (Hansen & Revellio 2020; Brito et al. 2022). Building supply chain resilience is also essential to ensure availability of spare parts and materials for efficient remanufacturing (Vogt Duberg et al. 2020).

BRIDGING THE GAP – EXPERT SURVEY FINDINGS

To better understand the practical implications of remanufacturing within Product-as-a-Service (PaaS) models, an expert survey was conducted to validate and expand upon the challenges and enablers previously identified through literature review. This survey served as a bridge between theoretical insights and real-world experiences, enabling a more grounded understanding of the landscape. A summary of the expert survey findings is presented in Figure 9.

12
KEY CHALLENGES

14
ENABLING FACTORS

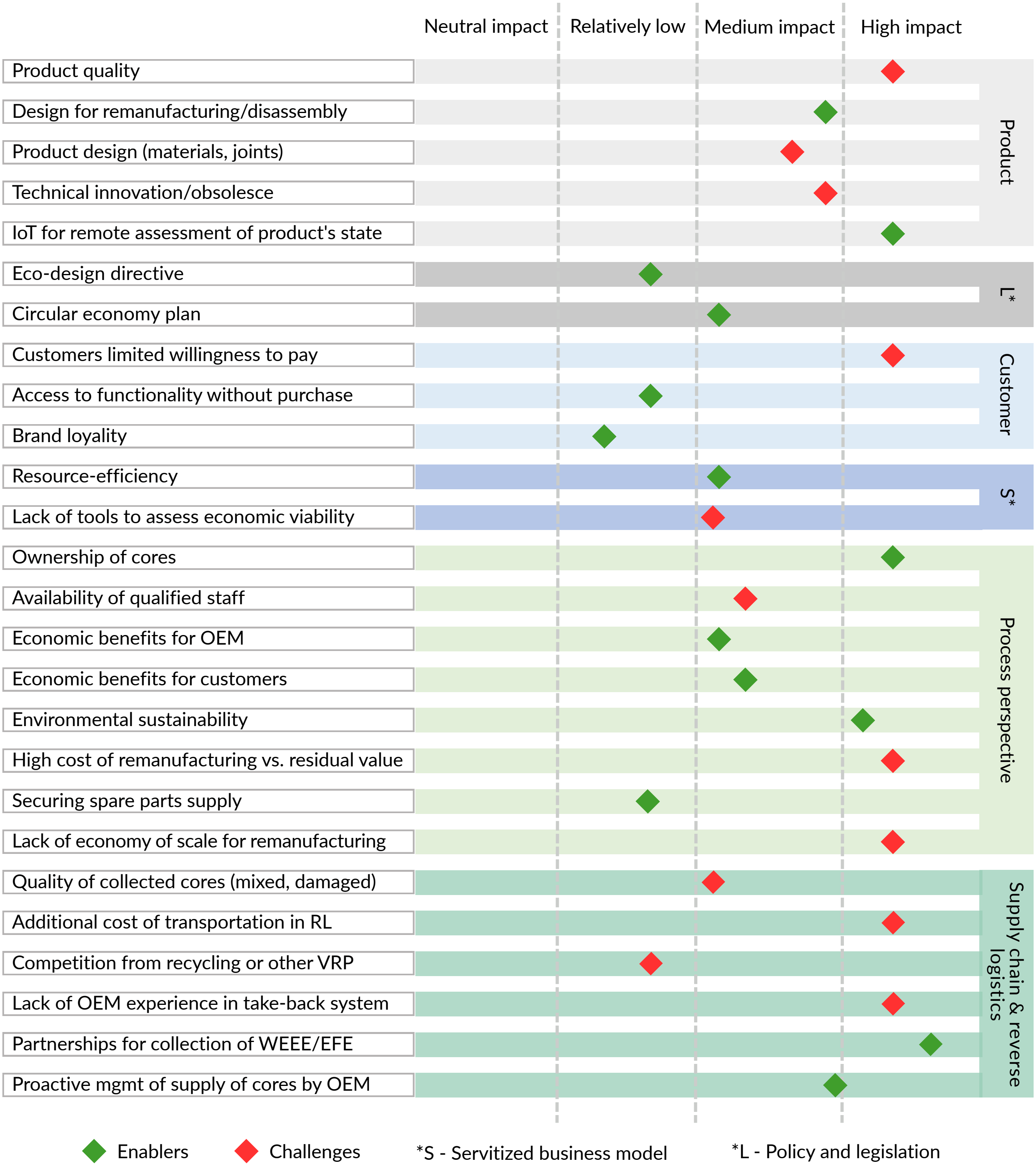


Figure 9. Significance of challenges (in red) and enablers (in green) based on (Golinska-Dawson et al. 2024)

Experts were asked to assess the relevance and completeness of the preliminary categories. Their feedback helped refine and consolidate overlapping issues while identifying new themes not fully captured in existing literature. Points of consensus were prioritised for deeper investigation, ensuring that the most pressing and widely recognised concerns were highlighted. As a result of this iterative process, a final list of 12 key challenges and 14 enabling factors was established. These outcomes provide a structured foundation for addressing barriers and supporting the implementation of circular strategies in PaaS ecosystems.

Based on expert evaluation, twelve challenges were identified in remanufacturing within Product-as-a-Service (PaaS) models for Electrical and Electronic Equipment (EEE). Of these, six were assessed as having a high impact, five as medium impact, and one as having relatively low but still noticeable impact (namely: competition from other value retention processes). The six high-impact challenges are described below:

1. Inadequate product quality of EEE

Most EEE products are designed with a predetermined, limited lifespan and with a focus on minimising production costs. Consequently, key components often lack the durability required for remanufacturing. This significantly limits the technical and economic feasibility of remanufacturing processes. These findings are consistent with earlier research which highlighted the poor suitability of many products for remanufacturing and the resulting economic constraints.

2. Low willingness to pay for remanufactured products

Consumers tend to value remanufactured products less than new ones, resulting in reduced willingness to pay. This market perception undermines the commercial viability of remanufacturing, particularly in B2C PaaS contexts, where consumer trust and pricing expectations are paramount.

One contributing factor is the widespread confusion surrounding product categories such as 'repaired', 'refurbished', and 'remanufactured'. Without clear definitions or consistent quality standards, consumer confidence remains low. Introducing regulatory standards and public incentives could help to shift these perceptions and may increase market uptake.

3. High cost of remanufacturing comparing to the residual value of a product

Remanufacturing processes often incur significant costs, including labour-intensive disassembly, inspection, part replacement and reassembly. These costs are not always justified by the residual value of the returned product. This can render remanufacturing economically unfeasible, especially when product quality is poor and demand is uncertain.

4. Lack of economy of scale in PaaS models

PaaS for EEE remains a niche model, particularly within the B2C sector, with the majority of implementations being confined to pilot or small-scale projects. This prevents OEMs from reaching the critical volume of returned products required for remanufacturing to be cost-effective. The lack of scale also hinders the development of robust, data-driven assessments of sustainability and profitability.

5. Additional reverse logistics costs

Reverse logistics in PaaS models introduces new, and often higher, costs for OEMs compared to traditional EEE collection systems. Unlike recycling schemes managed by specialised third-party providers, PaaS contracts require OEMs to take responsibility for collecting, sorting, refurbishing/remanufacturing and redistributing used products. These logistics burdens, especially at the end of service contracts, can significantly impact the business case for remanufacturing.

6. Lack of OEM experience in organising take-back systems

OEMs often lack the necessary expertise and infrastructure to manage product returns for remanufacturing effectively. Current take-back systems are typically designed with recycling in mind, not remanufacturing. Products are often collected in bulk and handled in ways that damage components, rendering them unsuitable for reuse. Improving the condition and traceability of returned products is essential, as the availability and quality of cores directly impact the feasibility and cost of remanufacturing.

Addressing these six critical challenges is essential for advancing scalable and sustainable remanufacturing within PaaS models for EEE. Each issue poses a technical or operational hurdle and affects broader systemic factors, including consumer acceptance, regulatory alignment and the performance of the circular economy. To enhance circularity in PaaS models, proactive product life cycle management is essential, ensuring the collection of products with high value at the end of use (EoU) rather than at the end of life (EoL).

Integrating remanufacturing within PaaS creates potential for increased resource efficiency by minimising the consumption of natural resources, critical raw materials, energy, and waste, thus preserving the embedded value of EEE from its initial production phase (Morseletto, 2020). Economic benefits in PaaS arise from the reuse of EEE components in multiple cycles (Gülserliler et al., 2022; Krystofik & Gaustad, 2018). In the EEE sector, extending product life contributes to sustainability by reducing the frequency of replacements (Boorsma et al., 2021). Furthermore, OEMs' commitment to environmental sustainability and green branding can incentivise the expansion of remanufacturing initiatives (Vogtlander et al., 2017).

For PaaS models to be economically viable, it is crucial that customers return products in good condition and within the designated contract period. This approach significantly reduces remanufacturing costs and facilitates economies of scale. Financial incentives, such as subsidies, could alleviate cash flow challenges while supporting the organisation of dedicated take-back systems and fostering collaborations across the value chain (Brito et al., 2022; Hansen & Revellio, 2020). Additionally, strengthening supply chain resilience is essential to ensure the availability of spare parts and materials for cost-effective and timely remanufacturing in PaaS models (Vogt Duberg et al., 2020).

Existing studies on remanufacturing in PaaS for electrical and electronic equipment (EEE) in consumer markets remain limited, with most findings derived from pilot projects initiated by OEMs (van Loon et al., 2022). A SWOT analysis of the development of remanufacturing in PaaS, based on a literature review and expert interviews, is presented below.

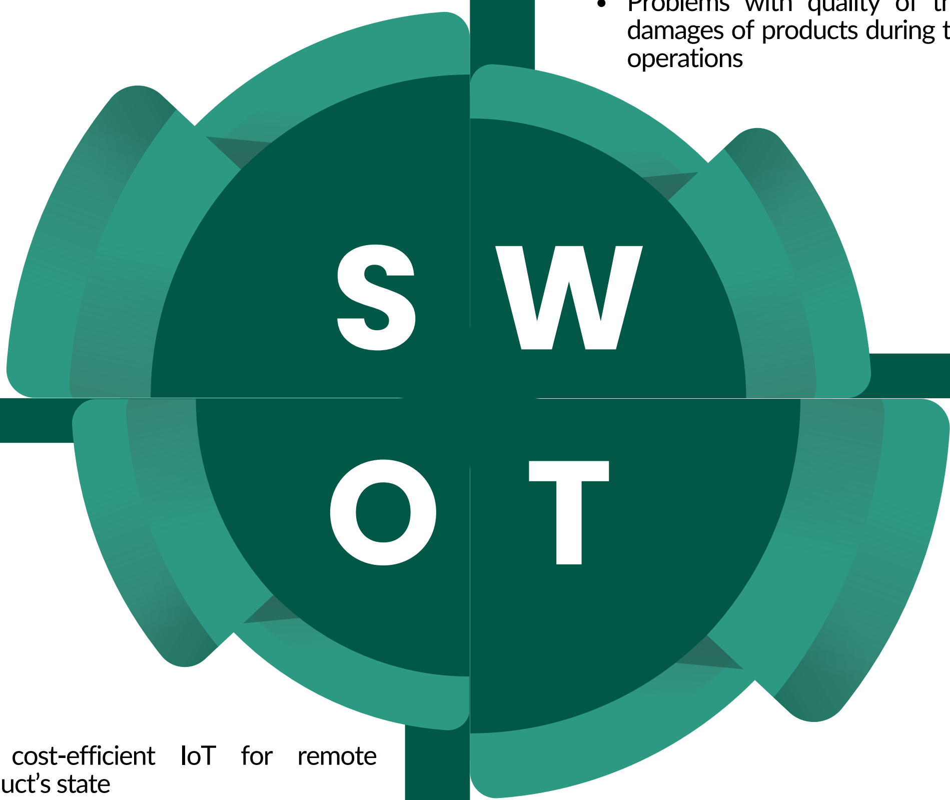
Swot Analysis

Strengths

- Control over cores by OEMs
- Potential to increase environmental sustainability
- Potential resource-efficiency through closing the loop in PaaS
- Potential economic benefits for OEMs through multiple PaaS contracts and new revenue streams, new sales channels, and consumer groups
- Ability to proactively manage cores
- Securing cost-efficient spare parts for maintenance and servicing

Weaknesses

- Quality of linear product not suitable for reman
- Potentially high cost of remanufacturing in comparison to product's residual value
- Low economy of scale for organising the economically viable remanufacturing process
- Additional transportation and storing costs in RL
- Lack of experience and expertise of OEM in organisation of the take-back system for PaaS
- Current product design practices (low level of approachability by design for remanufacturing)
- Limited tools to assess the economic viability of PaaS offer with remanufacturing
- Limited availability of skilled people for remanufacturing operations
- Problems with quality of the collected cores, damages of products during the reverse logistics operations



Opportunities

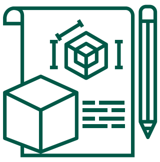
- Development of cost-efficient IoT for remote assessment of product's state
- Development of new partnerships for collection of WEEE/EEE
- Development of design for remanufacturing & non-destructive disassembly
- Application of new/desired economy plan with clear focus on PaaS models
- Promoting economic benefits for customers resulting from extended warranties and lower costs of maintaining and using the products (as they are covered by PaaS provider)
- Securing availability of spare parts for remanufactured products
- Increased brand loyalty by establishing direct communication with the customer through PaaS contact
- Promoting circular consumption with hassle-free access to products/shared products in PaaS

Threats

- Unknown/limited customer acceptance and willingness to pay for remanufactured products in PaaS
- High competition from recycling/other VRPs and a centralised take-back system, which are focused solely on recycling targets
- High speed of technological innovations, which increases the risk of the obsolescence of reman products in PaaS

To scale up remanufacturing in PaaS and overcome the related barriers, there is a need to develop the necessary capacities. In the literature, there are limited examples of capacity models for remanufacturing, especially in the context of PaaS. Capacity building for remanufacturing involves developing the infrastructure, technical expertise, and alignment with the business model to efficiently recover end-of-use or end-of-life products into remanufactured goods. The main recommendations derived from the expert's survey are presented below:

Enhancing Product Design for Circularity



To mitigate challenges related to product design in remanufacturing, OEMs may adopt modular design principles that facilitate ease of disassembly, modularity, component replacement, and material recovery. Design-for-remanufacturing (DfRem) methodologies should be embedded in product development processes, ensuring that components can be reused, replaced or upgraded efficiently. Additionally, the incorporation of standardised interfaces and interchangeable parts can further improve the feasibility of remanufacturing operations.

Optimizing the Cost-Effectiveness of Remanufacturing

As remanufacturing is labour-intensive, OEMs can enhance cost efficiency by focusing on automation and process optimisation techniques. The establishment of regional remanufacturing hubs can minimise transportation costs and reduce the environmental impact of logistics overall. Furthermore, digital technologies such as artificial intelligence (AI) and machine learning (ML) could be used to improve decision-making when assessing the economic viability of remanufacturing.

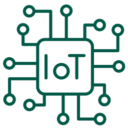
Improving Reverse Logistics and Collection Systems

Efficient reverse logistics (RL) is critical for ensuring a consistent supply of high-quality cores. To address current inefficiencies, OEMs can develop blockchain-enabled tracking systems for real-time monitoring of core returns. Partnering with specialised reverse logistics providers and implementing automated sorting and quality assessment mechanisms can significantly reduce the costs and complexity of handling of returned products.

Addressing Workforce Skill Gaps in Remanufacturing

The successful adoption of remanufacturing in PaaS requires a skilled workforce with expertise in disassembly, reassembly, and quality assurance processes. To address existing skill gaps, OEMs can invest in training programs, industry-academic collaborations, and professional certification initiatives. Establishing partnerships with universities and research institutions can further support knowledge transfer and innovation in remanufacturing techniques.

Leveraging IoT and AI for Smart Product Assessment



Integrating IoT-based predictive maintenance systems can enable remote monitoring of product condition, allowing OEMs to proactively determine the optimal timing for remanufacturing interventions. AI-driven analytics can further assist in assessing the feasibility of remanufacturing versus alternative value retention processes (VRPs), thereby enhancing decision-making efficiency.

Strengthening Customer Engagement and Acceptance of Remanufactured Products

A significant barrier to the adoption of remanufactured products in PaaS is limited consumer acceptance. To overcome this, OEMs could implement customer education initiatives emphasising the economic and environmental benefits of such products. Offering extended warranties and performance guarantees, as well as transparent communication regarding product reliability, could help to build consumer trust and acceptance.

Mitigating Competitive Pressures from Recycling and Alternative VRPs

The transition from traditional recycling focused strategies to remanufacturing driven circular economy models calls for clear differentiation of remanufacturing from other value recovery processes. Emphasising the lifecycle cost savings and high quality of remanufactured products can help build consumer trust and acceptance. Furthermore, developing premium remanufactured product lines with enhanced functionalities such as software upgrades and extended support services can strengthen the value proposition for consumers.

Addressing the Risk of Technological Obsolescence

Rapid technological advancements pose a risk to the viability of remanufacturing in PaaS. To mitigate obsolescence risks, OEMs can adopt upgradeable hardware architectures that enable component-level upgrades rather than full product replacements. Software-driven innovations, such as updates and cloud-based service enhancements, can further extend product lifespan and maintain competitiveness in dynamic technological landscapes.

4. CAPACITY BUILDING - KEY AREA AND MODEL STRUCTURE

4.1. KEY AREAS FOR CAPACITY BUILDING

Most OEMs, particularly those in the EEE sector, currently lack the capacity to incorporate remanufacturing into their existing manufacturing systems. Research shows that several challenges must be overcome before remanufacturing can be initiated (Duberg et al. 2023; Kurilova-Palisaitienė et al. 2020, 2024; Vogt-Duberg et al. 2023). In order to increase the scale of remanufacturing in the EEE sector within PaaS settings, companies must develop the necessary capacities at organisational and individual levels (i.e. among workers and managers).

Capacity building is defined as the process of developing and strengthening the skills, resources and processes of individuals and organisations, enabling them to achieve their goals effectively, solve problems and improve performance over time (UN, 2024). Consequently, capacity building for remanufacturing is defined as activities that help companies and their employees become more efficient and environmentally friendly in performing their remanufacturing processes.

In order to overcome the challenges associated with remanufacturing, original equipment manufacturers (OEMs) should prioritise improving product quality and durability, assessing customer willingness to pay, and setting up cost-efficient remanufacturing processes and reverse logistics systems. A crucial first step is to implement actionable approaches to assess product durability and quality, ensuring they are suitable for remanufacturing within the PaaS. This may be complemented by a greater emphasis on designing products for disassembly and making them more modular, to facilitate efficient end-of-life management. Furthermore, OEMs require analytical tools to better understand customer acceptance of, and pricing expectations for, remanufactured products within the PaaS model. Currently, the potential market size and acceptable price points are largely uncertain, which creates a barrier to scaling up remanufacturing efforts. Closing this knowledge gap is essential for making informed decisions and developing strategies. From a servitised business model perspective, OEMs should develop strategies that balance their own economic sustainability with the financial benefits delivered to customers.

In PaaS, customers pay for performance rather than product ownership; therefore, economic advantages shall be structured in a way that renders the distinction between remanufactured and new products irrelevant. This shift has the potential to significantly expand the market share of remanufactured electrical and electronic equipment (EEE). One of the primary obstacles to remanufacturing within PaaS is the cost-effective organisation of the process. Currently, standardised cost models for remanufacturing in PaaS are lacking, and OEMs often have limited prior knowledge regarding the relevant cost categories and their associated values. To address this, the development and implementation of novel tools are required to estimate product residual value. That can enable informed decisions on whether remanufacturing is economically viable for subsequent PaaS cycles or whether products should be redirected to recycling.

Additionally, OEMs require support in determining the necessary production volumes to achieve economies of scale in remanufacturing. To enhance decision-making, practical tools should be introduced for collecting and analysing data on reverse logistics costs. OEMs must be equipped with mechanisms to evaluate whether to establish own take-back systems or participate in collaborative initiatives. Furthermore, exploring incentive structures to foster partnerships in take-back systems can enhance the efficiency and feasibility of remanufacturing operations.

To address the identified challenges for remanufacturing in PaaS we propose a novel Rem-Cap-Up model, which is structured as presented in Figure 10.

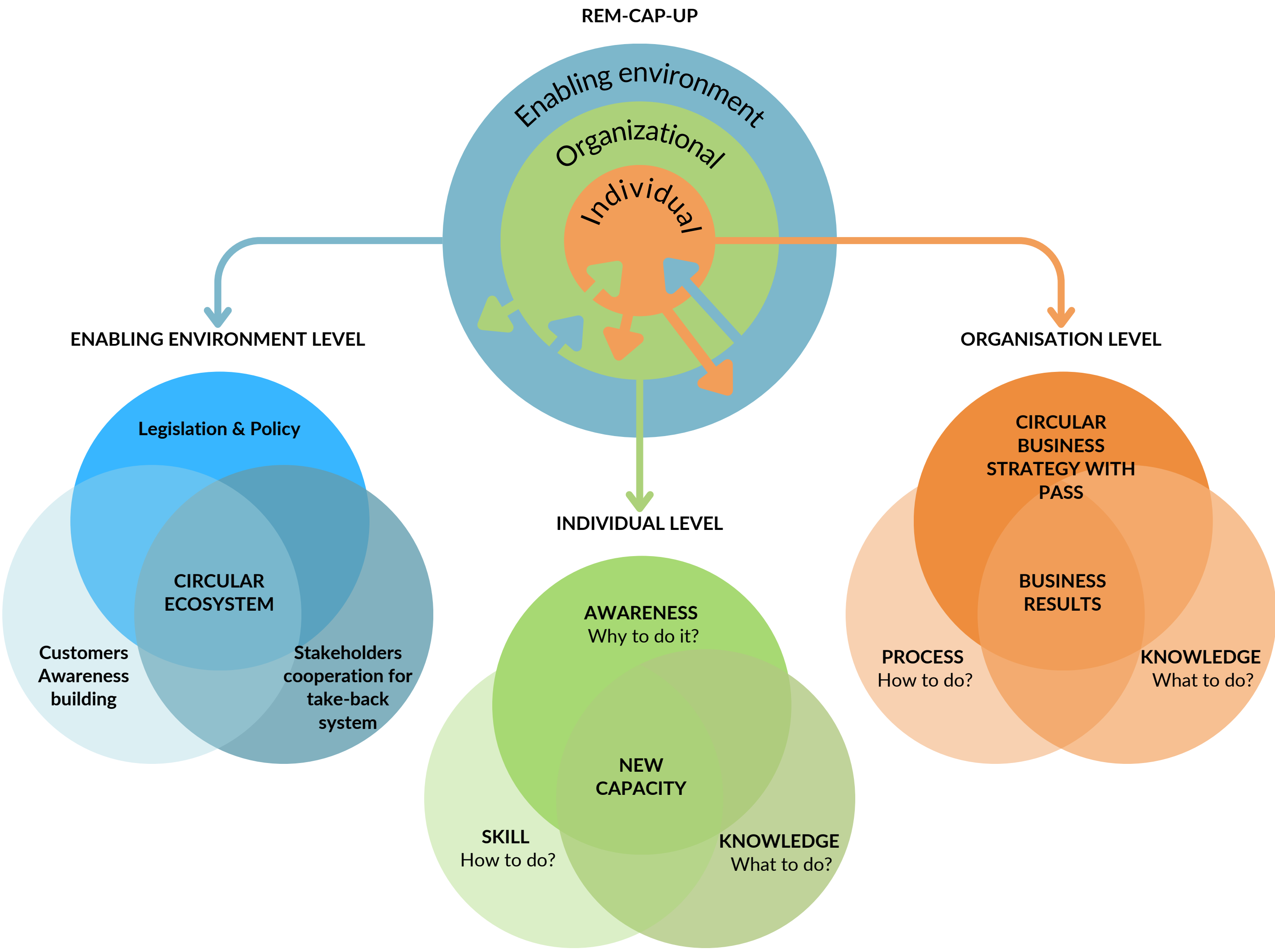


Figure 10 - Rem-Cup-Up model (inspired by FAO, 2024)

The model includes:

- Individual Level: The focus is on developing the essential competencies of employees and managers across three organisational tiers: operational (employees engaged in remanufacturing and related processes), tactical (middle management), and strategic (business owners, senior management, etc.). The model follows a structured, progressive framework that begins with awareness creation, advances through knowledge development, and culminates in the continuous enhancement of skills.
- Organisational Level: The emphasis is on developing the necessary resources, optimising cost-efficient remanufacturing processes, and aligning them within the Product-as-a-Service (PaaS) business model and circular strategy.
- Enabling Environment Level: The focus is on fostering collaboration with business partners to establish an efficient take-back system, enhancing customer commitment to PaaS, and increasing consumer acceptance and willingness to pay for remanufactured products within the PaaS framework. Additionally, this level includes advocacy efforts through industry associations to promote necessary policy shifts that support remanufacturing and the broader adoption of the PaaS model.

4.2. APPLYING REM-CAP-UP IN PRACTICE

The practical application of Rem-Cap-Up provides companies with a structured approach to evaluate their current capacity for remanufacturing within a Product-as-a-Service (PaaS) model. The model provides a comprehensive framework to assess organisational capacity, covering the dimensions of resources, processes, and circular business strategy, as well as individual capacity. This focuses on the awareness, knowledge, and practical skills of employees at the operational, tactical, and strategic levels.

There are relatively few examples of capacity models for remanufacturing in the context of circular business models. The key areas of the capacity building can be grouped as:

- Developing infrastructure and technical resources, including facilities for the disassembly, reprocessing, and reassembly of products (Kurilova-Palisaitiene et al. 2024)
- Developing skills, including training programs and initiatives to enhance the skills of the workforce in remanufacturing processes (Chigbu et al. 2024), especially in using the advance modern technologies (e.g. additive manufacturing) (Alghamdi et al. 2017; Bressanelli et al. 2017; Panagou et al. 2023); and applying smart technologies to recover, process, and analyse product life cycle information (Mejía-Moncayo et al. 2023; Nwankpa et al., 2023)
- Improving the suitability of the product for remanufacturing through Design for R and increased durability and reparability (Boorsma et al. 2021; Hilton, 2024).
- Mastering the reverse logistics (Kurilova-Palisaitiene et al. 2024; Vogt Duberg et al. 2023)
- Understanding market demand for remanufactured products and educating consumers about their benefits and willingness to pay (Koller et al., 2020; Kurilova-Palisaitiene et al., 2024)
- Understanding quality standards to ensure the reliability and acceptance of remanufactured products and legislation for circularity (Wasserbaur et al. 2022).

The Rem-Cap-Up model is applied to address the key capacity-building areas identified through a systematic literature review (for details see: Golińska-Dawson et al. 2024), PaaS business model development workshops with Original Equipment Manufacturers (OEMs) in the household appliances sector (for details see: Hidalgo-Crespo et al. 2024), media listening and an industry practices review (for details see: Golińska-Dawson, Pender and Zysnarska 2024). The identified capacities are cross-referenced with the challenges and enablers in the following categories: Product; Legislation; Customers and Market; Servitised Business Model; Process and Technology; Supply Chain and Take-Back System.

By examining each area in depth, Rem-Cap-Up enables organisations to identify specific gaps that may hinder their transition to a circular economy. It also facilitates a combined assessment, providing a comprehensive view of an organisation's overall readiness. This approach supports targeted planning, informed decision-making and prioritisation of actions to effectively bridge organisational and individual capacity gaps, ultimately driving the successful implementation of circular practices.

The self-assessment follows the logic (full procedure available in Appendix):

1. Start the Assessment
   Initiate the process by preparing internal teams for data collection.
2. Collect Data
   - Distribute and complete two surveys:
     - Employee Capacity Assessment (individual-level skills, knowledge, and awareness)
     - Organisational Capacity Assessment (resources, processes, strategy)
3. Calculate Capacity Indices
   - Calculate:
     - Individual Capacity Index (ICI) – for operational, tactical, and strategic levels.
     - Organisational Capacity Index (OCI) – for overall organisational capability.
4. Classify Capacity Levels
   Use the ICI and OCI scores to classify capacity:
   - <20% – No or Very Low Capacity (Level 1)
   - 20–40% – Low Capacity (Level 2)
   - 40–60% – Intermediate Capacity (Level 3)
   - 60–80% – High Capacity (Level 4)
   - >80% – Full Capacity (Level 5)
5. Analyse Results and Select Strategy
   Based on the classification:
   - Identify specific gaps (awareness, skills, resources, etc.).
   - Determine which area (employee and/or organisational) needs development.
6. Implement Development Actions
   - For employees: focus on building awareness, knowledge, and skills.
   - For organisation: develop resources, processes, and business strategy for PaaS.
7. Monitor and Re-assess
   - Track progress through regular follow-ups.
   - Reassess to measure improvement and adjust actions accordingly.

The overview of the self-assessment areas is presented in Figure 11.

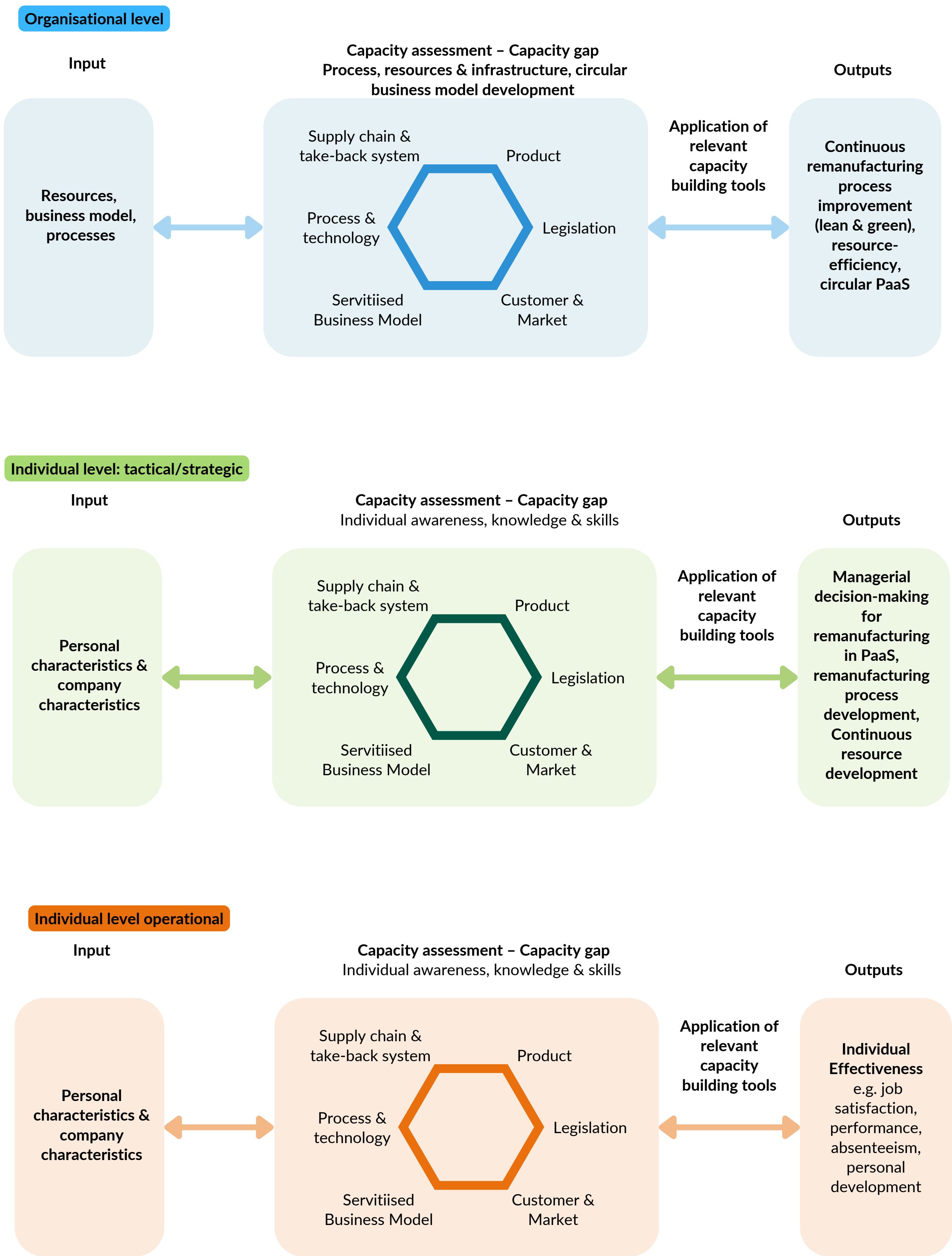


Figure 11. Dimension of the capacity gaps in Rem-Cap-Up model

4.2.1. ASSESSMENT OF INDIVIDUAL CAPACITY GAP

In order to identify the hotspots for remanufacturing capacity building, there is need to assess the current state and to identify the gaps which shall be filed. It requires a closer look first into the individual capacities of employees at:

- Operational – line workers, logistics workers
- Tactical – line managers, middle management
- Strategic level – senior management, business owners.

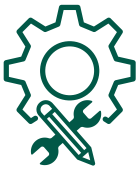
There individual capacities are described by their:

LEVEL OF AWARENESS OF REMANUFACTURING ISSUES

When employees aren't aware of remanufacturing and PaaS → that's an awareness gap.

LEVEL OF PROFESSIONAL KNOWLEDGE

When employees don't understand how a remanufacturing and PaaS works → that's a knowledge gap.



LEVEL OF PRACTICAL SKILLS

If employees know the theory but can't perform remanufacturing tasks in PaaS correctly → that's a practical skills gap.

In the Rem-Cap-Up model together with industrial partner, we test those capabilities to define different levels of them:

- Level 1: no awareness, no knowledge, no experience
- Level 2: limited awareness, basic knowledge, minimal experience (training phase/ supervision needed)
- Level 3: intermediate awareness, practical knowledge, intermediate experience
- Level 4: high awareness, specialised (practical and theoretical) knowledge, significant experience
- Level 5: full awareness, expert knowledge, extensive experience (expert)

What is capacity gap regarding employees?
A capacity gap at individual level includes awareness, knowledge, and practical skills of employees.
It is the difference between:

What an employee currently knows or can do	VS.	What an employee should know or be able to do to perform their job effectively

Capacity gap is the missing piece between where empoyees are and where they need to be with regard to remanufacturing in PaaS

The capacity gap at individual level shows the difference between the current state and the reference Level 5. The example of the self-assessment tool can be found in Table 4. The assessment scheme includes a set of questions on scale 1 (min)-5 (max), where:

Table 4. How to assess the level of individual capacity?

Ranking grade	Awareness	Knowledge	Skills
1	I have no awareness in this area	I have no knowledge in this area	I have no practical experience in this area
2	I have limited awareness in this area	I have basic knowledge in this area	I have minimal experience (training phase/need supervision) in this area
3	I have an intermediate awareness in this area	I have practical knowledge in this area	I have intermediate experience in this area
4	I have a high level of awareness in this area	I have specialized (practical and theoretical) knowledge in this area	I have significant experience in this area
5	I have full awareness in this area	I have an expert knowledge in this area	I have extensive experience (I am an expert) in this area

The set of areas and categories is relevant for all levels of staff, from operational, tactical, to strategic. The expectations for awareness, knowledge, and skills differ depending on the level of decision-making. The set of capabilities for the strategic level is presented in the Table 5 below.
Legend: P - products; L - legislation; C-customers &market; B- servitised business model; PR- remanufacturing process; SC&RL- supply chain and reverse logistics.

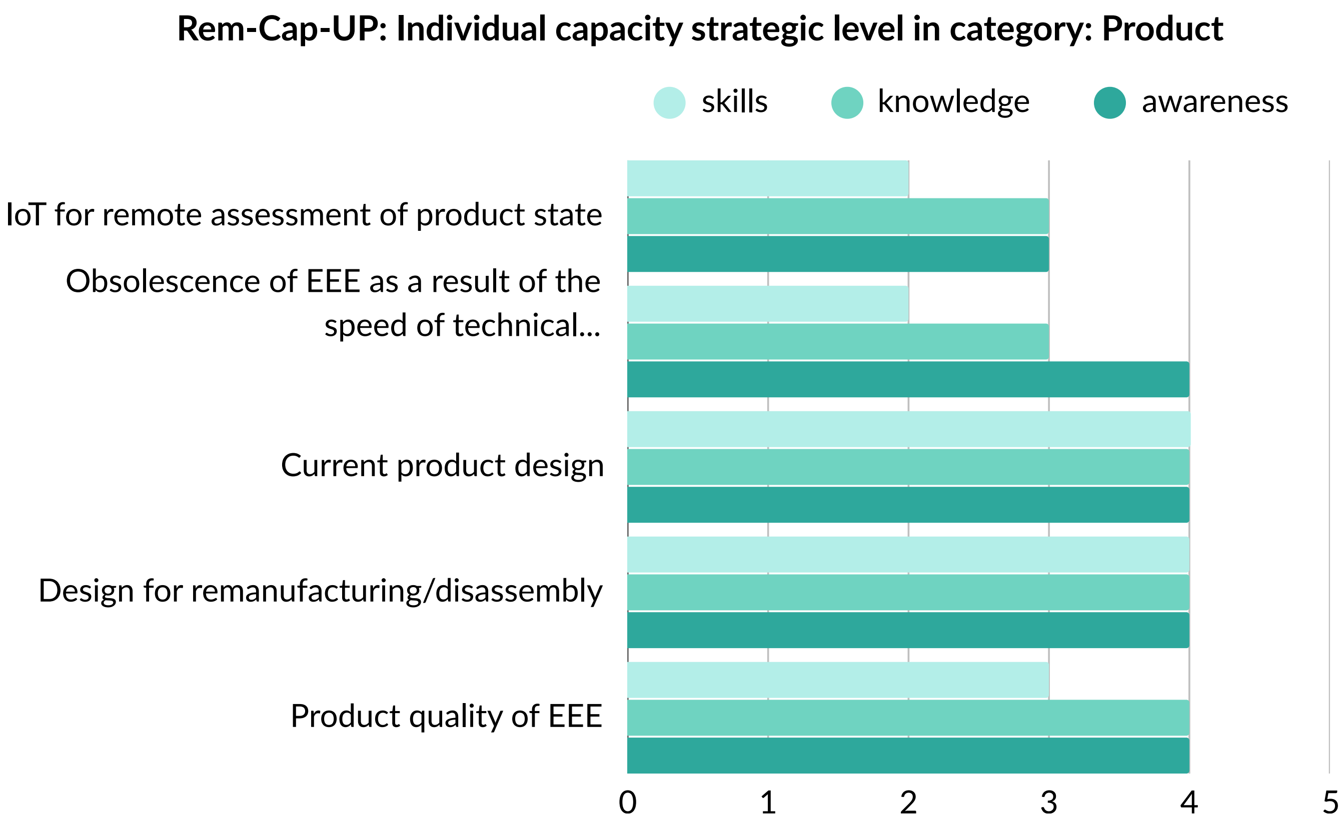
Table 5. Assess your capacity in the remanufacturing process

		Awareness					Knowledge					Experience				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
P1	Increasing durability and quality of key components to support remanufacturing															
P2	Implementing product design for remanufacturing & easy disassembly															
P3	Reviewing the current design of EEEs in B2C suitability for remanufacturing															
P4	Technological innovations in EEE impact the cost effectiveness of remanufacturing															
P5	Applying IoT technology in remote assessment of porducts															
L1	EcoDesign to support modularity for reducing remanufacturing costs and achieving economies of scale															
L2	Adopting Circular Economy Action Plan (2020) with PaaS model as a key enabler of the circular transformation															
C1	Ensuring quality standards in the remanufacturing process to increase customers' willingness to purchase remanufactured products															
C2	Providing acess to product's functionality without the traditional sales															
C3	Using PaaS model to support customer loyalty towards the brand															

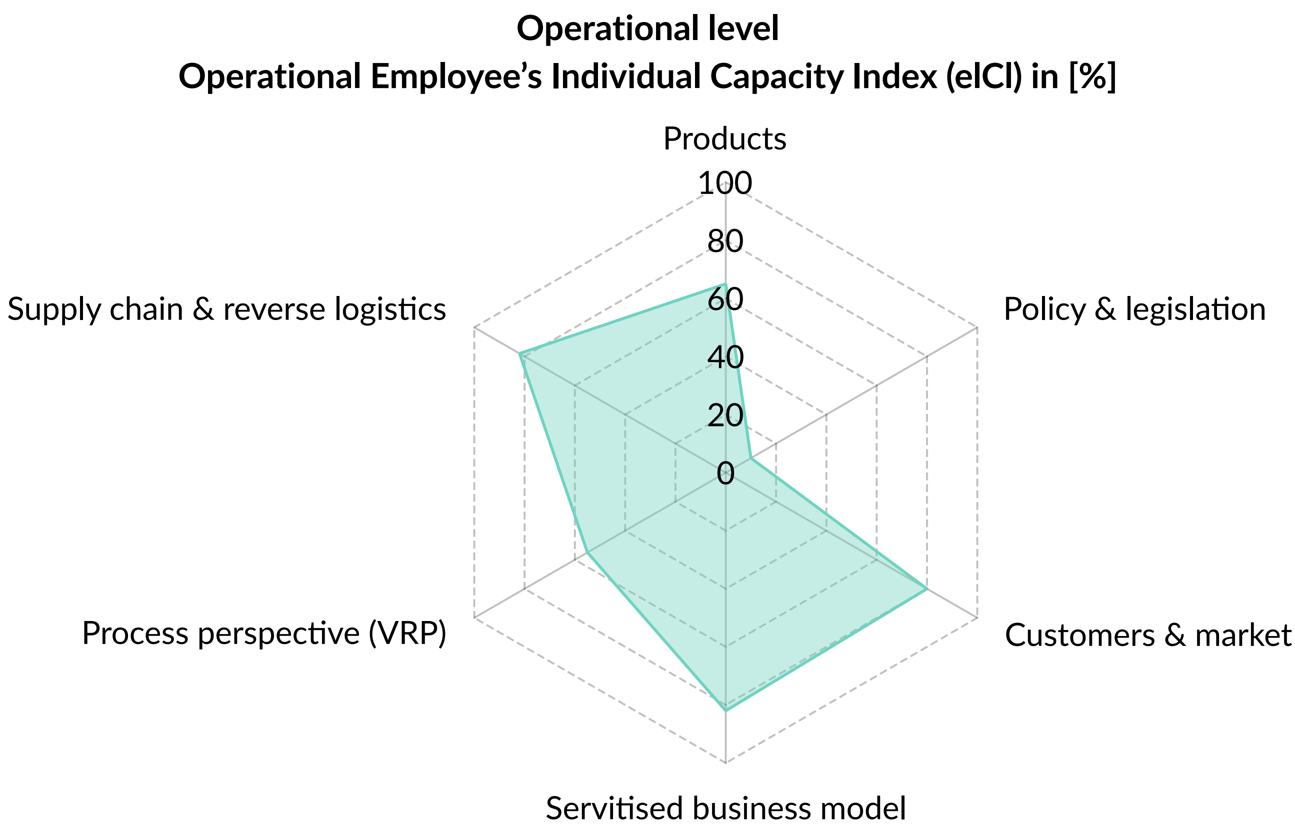
		Awareness					Knowledge					Experience				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
B1	Measuring the impact of the complexity of disassembly, and that easy, non-destructive disassembly processes and comparing the ease of disassembly in manual, robotic, and human-robot collaboration operations															
B2	Using tools such as LCA/LCC for calculations in PaaS															
PR1	Retaining ownership and control over the products, to benefit from the information on product returns (quantity, quality, and timing)															
PR2	Monitoring the necessary qualifications to perform the remanufacturing process															
PR3	Developing non-destructive disassembly related to the remanufacturing process to bring economic benefits															
PR4	Optimising the maintenance and service costs															
PR5	Comparing the materials and energy saving for end-of-use scenarios to achieve environmentally viable recovery of EEE products															
PR6	Assessing the remanufacturing cost in comparison to residual value of products															
PR7	Using non-destructive disassembly related to the remanufacturing as a source of cost-effective spare parts for servicing and maintaining products during PaaS															
PR8	Aiming for economy of scale for remanufacturing															

		Awareness					Knowledge					Experience				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
SC& RL1	Assessing core quality depending on time and user return behavior, and EEE regulations (may require recycling instead of remanufacturing).															
SC& RL2	Calculating additional costs related to collecting used products from customers, sorting, remanufacturing them, and delivering to new customers under future contracts															
SC& RL3	Assessing competition from recyclers and other value recovery providers (VRPs) in the context of economies of scale															
SC& RL4	Improving collection and transportation methods of (W)EEE to prevent damage and enhance their suitability for remanufacturing															
SC& RL5	Building partnerships in (W)EEE collection to support optimal recovery options in PaaS—such as remanufacturing, repair, reuse, or recycling—and to determine whether to handle remanufacturing in-house or outsource															
SC& RL6	Developing proactive core management															

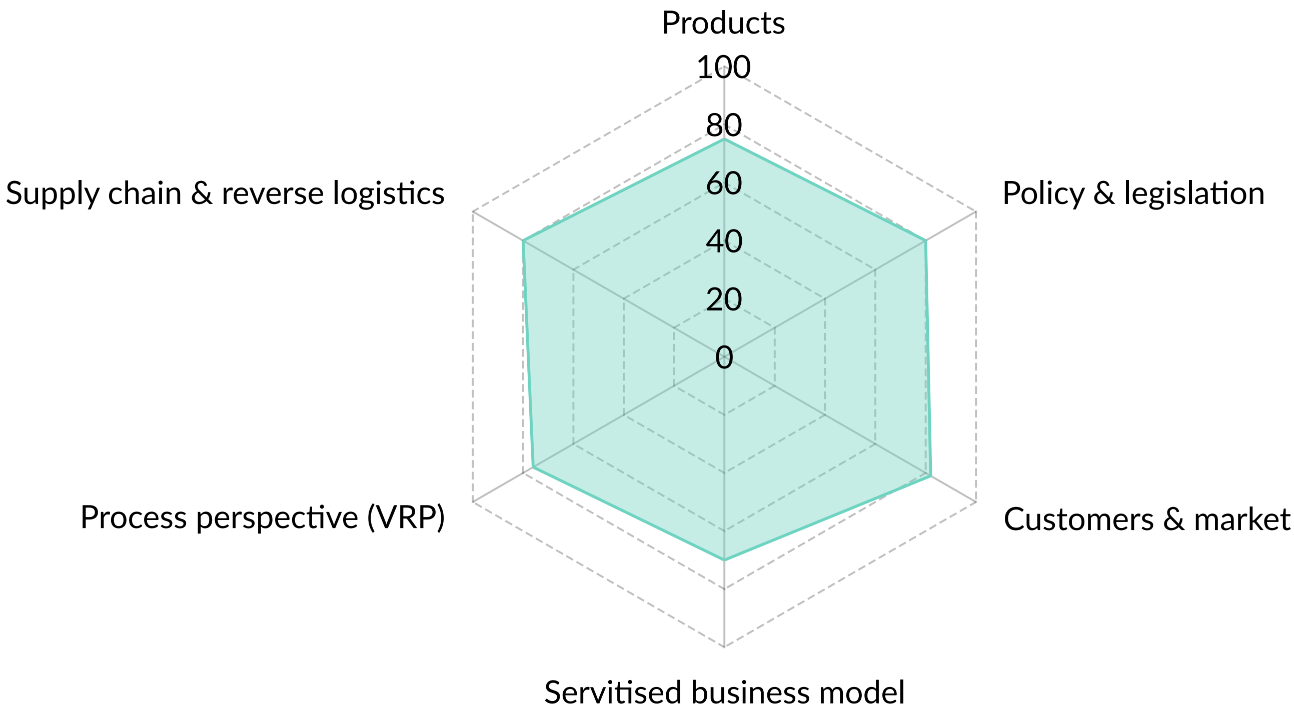
The example of the presentation of the results of individual capacity assessment for a chosen category is presented in Figure 12 below.



The results of the self-assessment highlight the capacity gap in each category for each level of staff.



Tactical level
Manager's Individual Capacity Index (mICI) [%]



Strategic level
CEO's / owner's Individual Capacity Index (oICI) [%]

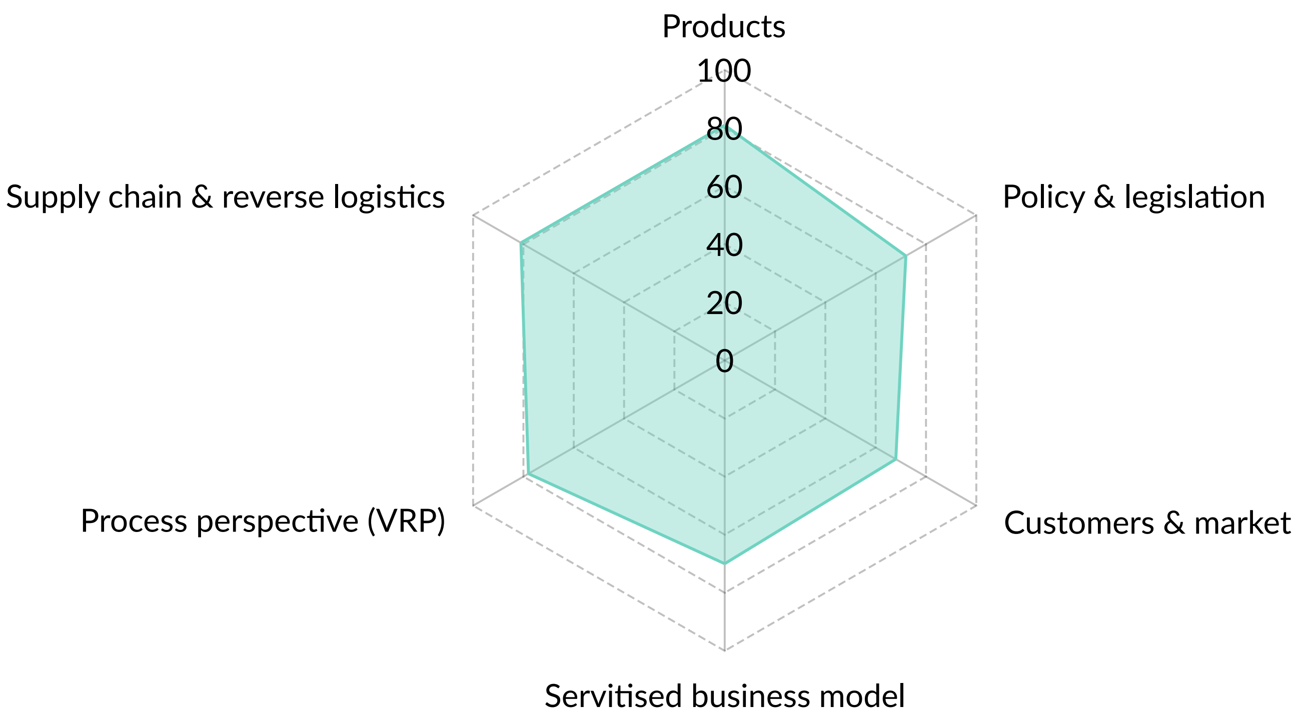


Fig 12. Capacity gap - example of assessment results

4.2.2. ASSESSMENT OF ORGANISATIONAL CAPACITY GAP

The capacity is also being developed at the organisational level in order to create the necessary framework for remanufacturing in PaaS by:

- Resources
- Processes
- Circular business strategy.

In the Rem-Cap-Up model, the organisational capacities are assessed according to the levels:

- Level 1: Lack of resources, remanufacturing process, and business strategy incorporating circular practices.
- Level 2: Fragmented resources, informal remanufacturing process, and a partially developed business strategy with some adoption of circular practices.
- Level 3: Dedicated resources, repeatable remanufacturing process, and a clearly defined business strategy integrating circular practices.
- Level 4: Dedicated resources aligned with the PaaS model, formalised and repeatable remanufacturing process within the PaaS framework, and a business strategy that incorporates circular practices through the PaaS model.
- Level 5: Fully dedicated resources within the PaaS model, with a strong focus on Lean and Green solutions; repeatable, formalised processes optimised remanufacturing for Lean and Green principles within the PaaS model; and a business strategy that systematically supports continuous improvement and innovation within the PaaS and circular economy framework.

ORGANISATIONAL CAPACITY MATURITY LEVELS FOR REMANUFACTURING IN PAAS

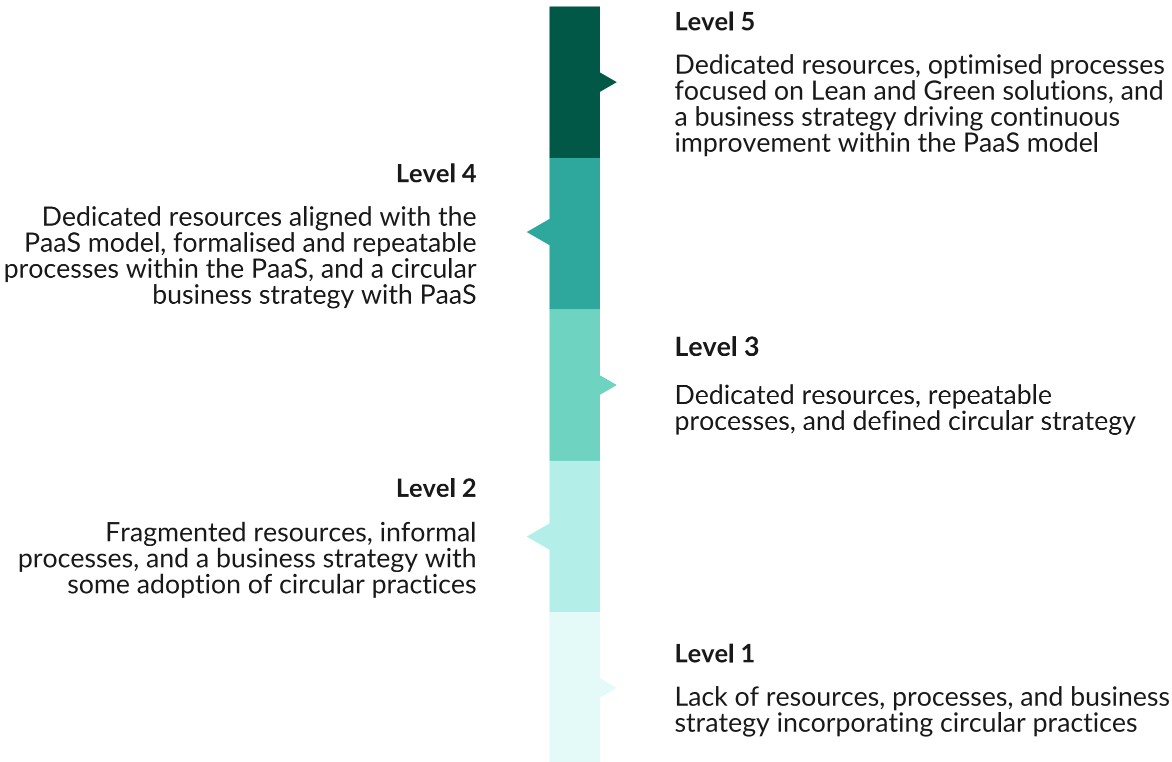


Fig. 13. Levels of capacity building at the organisational level including resources, process and circular strategy

The organisation capacity gap shows the difference between the current state and the reference Level 5. The example of the self-assessment tool can be found in Table 6. The assessment scheme includes a set of questions on scale 1 (min)-5 (max), where:

Table 6. How to assess the level of organisational capacity?

Ranking grade	Resources	Process	Circular Strategy
1	Lack of resources for this action	Lack of a process	Lack of business strategy incorporating circular practices
2	Fragmented resources for this action	Informal processes	Partially developed business strategy with some adoption of circular practices
3	Dedicated resources for this action	Formalised and repeatable processes	Clearly defined business strategy integrating circular practices
4	Dedicated resources for this action in the PaaS model	Formalised and repeatable processes within the PaaS framework	Business strategy that incorporates circular practices through the PaaS model
5	Dedicated resources for this action in the PaaS model, focused on Lean & Green solutions	Formalised processes optimised for Lean and Green principles within the PaaS model	Business strategy that systematically supports continuous improvement and innovation within the PaaS and circular economy framework

The capacities at the organisational level are measured in the same six areas and categories but using a different measurement tool. The set of areas and categories for assessment of the organisational capacity is presented in the Table 7 below.

Table 7. Assessment of the organisational capacity in the remanufacturing process

		Resources					Process					Circular Strategy				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
P1	Assessment of the durability and quality of key components for remanufacturing															
P2	Assessment of whether the product design allows for non-destructive disassembly of the product															
P3	Implementation of the remanufacturing process that takes into account the product structure															
P4	Assessment of the cost-effectiveness of remanufacturing in terms of the technological innovation of the product															
P5	Remote assessment of the product's condition															

		Resources					Process					Circular Strategy				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
L1	Design EEE for remanufacturing and modularity to reduce costs and achieve economies of scale.															
L2	Implementation of circular practices (remanufacturing, refreshing, repair)															
C1	Implementation of quality standards in remanufacturing to increase customers' willingness to purchase regenerated products															
C2	Offering access to product functionality without traditional sales															
C3	Providing PaaS model to support customer loyalty towards the brand															
B1	Evaluation of remanufacturing efficiency based on disassembly complexity, highlighting easy, non-destructive processes for EEE, and using tools to compare manual, robotic, and human-robot disassembly															
B2	Calculation of enviromental and economic benefits by using tools like LCA/LCC															

Legend: P - products; L - legislation; C - customers & market; B - servitised business model; PR - remanufacturing process 7 technology; SC&RL - supply chain and take-back system

		Resources					Process					Circular Strategy				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
PR1	Retaining product ownership and control to leverage data on returns (quantity, quality, timing).															
PR2	Development of human resources to perform remanufacturing															
PR3	Development of economically viable, non-destructive disassembly methods for remanufacturing															
PR4	Development of economically viable maintenance and servicing in PaaS															
PR5	Assessment of material and energy saving potential for economically and environmentally viable recovery of EEE															
PR6	Assessment of remanufacturing costs in comparison to the product's residual value															
PR7	Development of non-destructive disassembly in remanufacturing to provide cost-effective parts for servicing in PaaS															
PR8	Development of economy of scale in the remanufacturing process															

Legend: P - products; L - legislation; C - customers & market; B - servitised business model; PR - remanufacturing process 7 technology; SC&RL - supply chain and take-back system

		Resources					Process					Circular Strategy				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
SC& RL1	Assessment of core quality based on return timing and user behavior, with some EEE subject to regulations that may direct them to recycling instead of remanufacturing															
SC& RL2	Assessment of additional costs related to collection, transportation, sorting, remanufacturing, and delivery of used products under subsequent contracts															
SC& RL3	Mitigating competition from recycling and other VRPs.															
SC& RL4	Development of WEEE collection practices that minimise damage during transport to preserve remanufacturing potential															
SC& RL5	Development of partnerships for WEEE collection to support remanufacturing															
SC& RL6	Development of proactive core management for an efficient remanufacturing process															

Legend: P - products; L - legislation; C - customers & market; B - servitised business model; PR - remanufacturing process 7 technology; SC&RL - supply chain and take-back system.

The results of the self-assessment highlight the capacity gap in each category in the context of the development of an economically viable and environmentally friendly remanufacturing process in PaaS. Visualisation of the organisational capacity gap is presented in Figure 14.

Rem-Cap-UP: Organizational capacity in category: Supply chain & reverse logistics

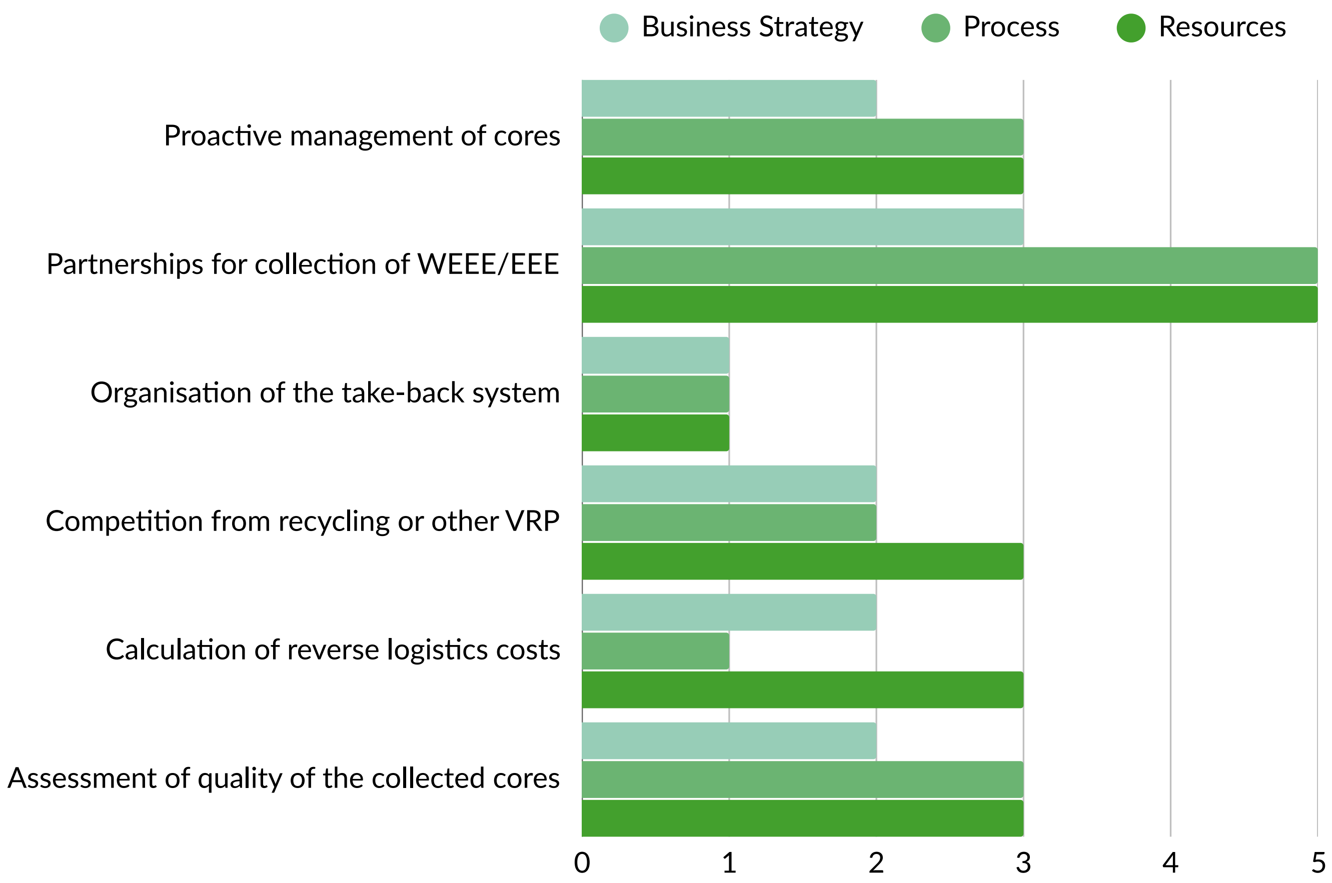


Figure 14. Example of the identification of organisational capacity for a chosen category

The results of self-assessments can be aggregated into (see Figure 15):

- Individual capacity index (ICI) – represents a composite measure that consolidates the assessment of individual capacities across all areas and categories for all staff levels involved in the self-assessment. It provides a single numerical value, expressed as a percentage, that reflects the overall level of awareness, knowledge, and practical experience of employees at the operational, tactical, and strategic levels. This percentage is then compared against a reference benchmark of 100%, which represents the ideal or expected level of capacity particularly in the context of remanufacturing in Product-as-a-Service (PaaS) models
- Organisational capacity index (OCI) – represents a composite measure that aggregates the assessment results of organisational capacity across three key dimensions: resources, processes, and circular business strategy. It provides a single numerical value, expressed as a percentage, which reflects the organisation's overall maturity in implementing circular practices, particularly in the context of remanufacturing and Product-as-a-Service (PaaS) models. This percentage highlights the gap between the actual and desired capacity, offering a clear metric for identifying improvement needs and tracking progress in bridging the organisational capacity gap.

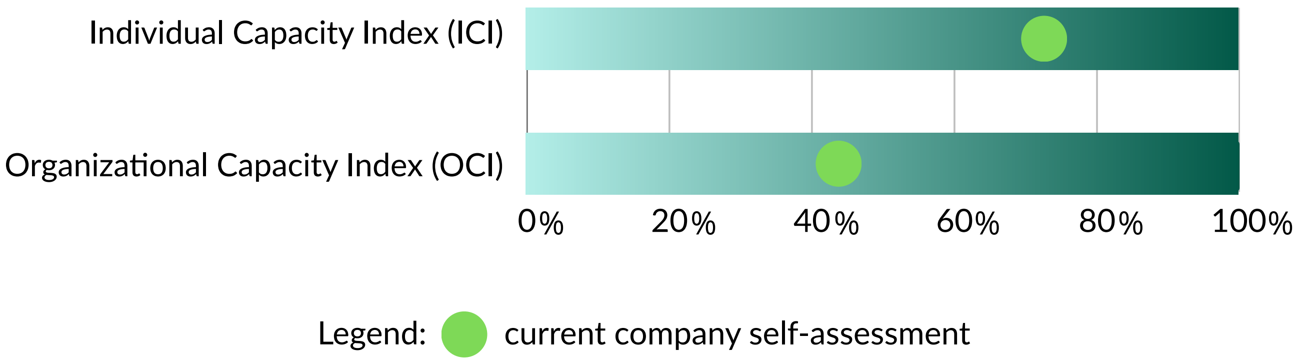


Figure 15 - Identification of overall capacity gap

4.2.3. TOOLS FOR BRIDGING THE CAPACITY GAP

A wide range of tools can be applied to bridge the capacity gap. Please refer to Figure 16 for a selection of tools.

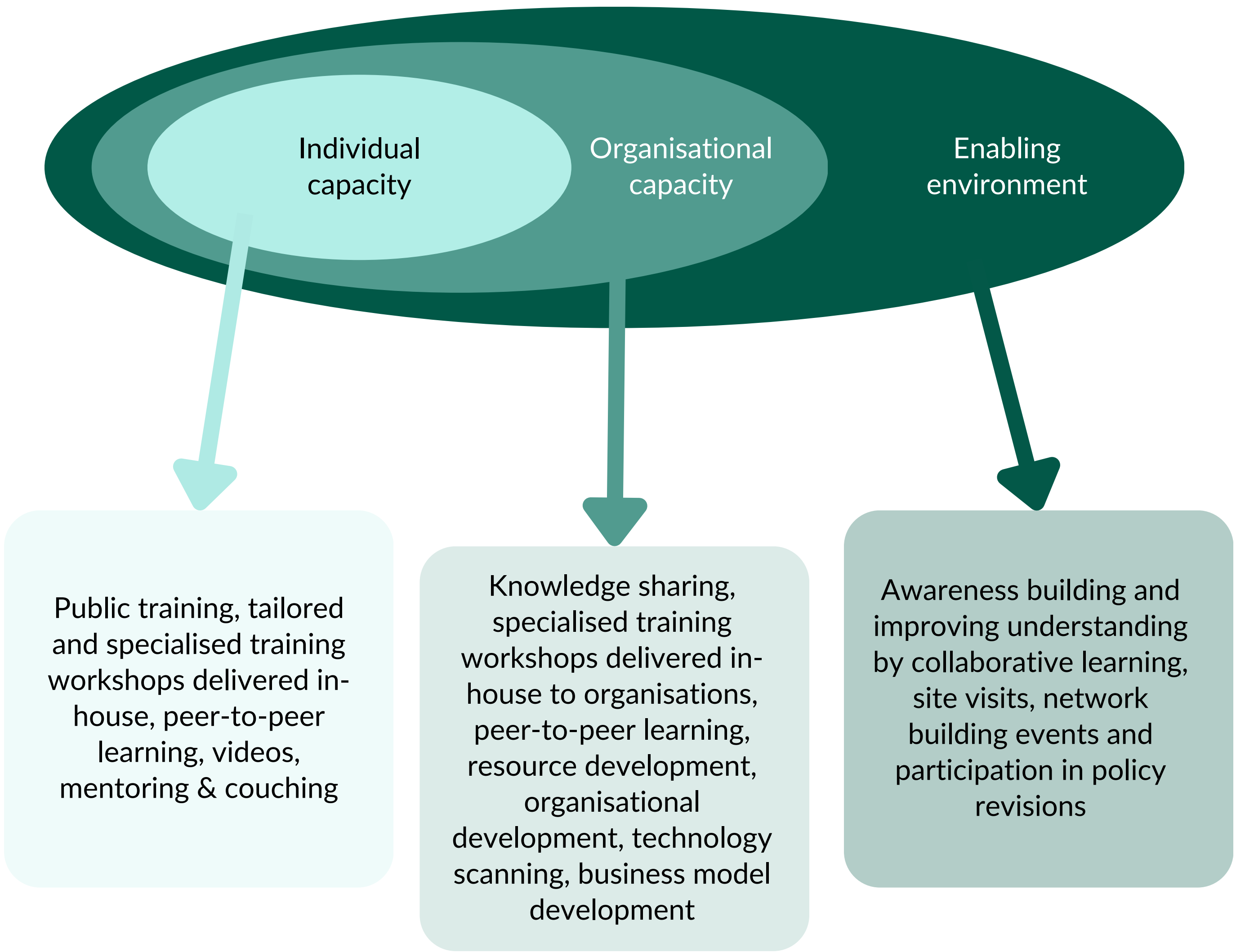


Figure 16 - Capacity development tools developed based on (Brown et al. 2001; Clearwater 2024)

The capacity development tools:

TRAINING AND EDUCATION

(Public or Customized Programs)

Delivering targeted learning opportunities to enhance specific skills and knowledge, ensuring competency development across relevant domains. These programs integrate collaborative learning approaches, such as peer discussions, interactive workshops, and cross-functional training, to facilitate knowledge exchange and practical skill application on remanufacturing, in particular on the non-distractive disassembly and quality assessment.

MENTORING AND COACHING

Providing structured guidance and support from experienced employees to facilitate knowledge transfer on remanufacturing and PaaS, skills enhancement, and professional development. This approach encourages collaborative learning through personalized feedback, shared experiences, and continuous learning networks.

RESOURCE DEVELOPMENT

Ensuring access to essential tools, equipment, and resources required to strengthen capacity and enhance operational efficiency in remanufacturing.

ORGANISATIONAL DEVELOPMENT

Enhancing internal structures and processes, including management strategies, communication frameworks, and human resource management systems, to improve overall organizational effectiveness. Awareness-building strategies are embedded within organisational change efforts to cultivate a shared understanding of best practices, industry trends, and the benefits of continuous improvement.

PARTNERSHIPS AND NETWORKING

Establishing collaborative alliances with organisations, institutions, and communities to foster resource-sharing, knowledge exchange, and collective problem-solving. These networks serve as platforms for collaborative learning, enabling the dissemination of best practices and fostering a culture of continuous improvement. Additionally, strategic partnerships contribute to awareness-building efforts, increasing stakeholder engagement and promoting broader adoption of circular business models.

Product-as-a-Service (PaaS) is a viable model that can help to reduce environmental impact and improve customer value. The transformation of business models from product-centric to service-oriented strategies should be a key priority. This change has implications for product design and customer relationships, as well as the realignment of internal operations and employee competencies. To address this, companies should begin with a structured capacity assessment using tools such as the Rem-Cap-Up model. This model enables organisations to evaluate both individual (employee) and organisational capacities by identifying gaps in awareness, knowledge, skills, processes, resources, and strategic alignment. For instance, if organisational capacity in reverse logistics or employee knowledge of value-retention processes (VRPs) is found lacking, targeted training or strategic partnerships can be initiated.

The Business Model Canvas (BMC) can be used to develop a business model tailored to PaaS by mapping value propositions, as well as the necessary resources, processes and partnerships. Companies should ensure their models support multiple customer usage cycles and incorporate robust take-back systems and durable product design. Although subscription and pay-per-use models offer unique advantages, both require a fundamental rethink of how value is created, delivered and sustained throughout the product lifecycle. Figure 17 presents an example of Business Model Canvas development for PaaS in the consumer electronics and electrical appliances (EE&A) sector. As the BMC is a conceptualisation tool, the Scandere project recommended following up on the initial ideas with take-back system assessment and life-cycle costing to achieve more tangible results.

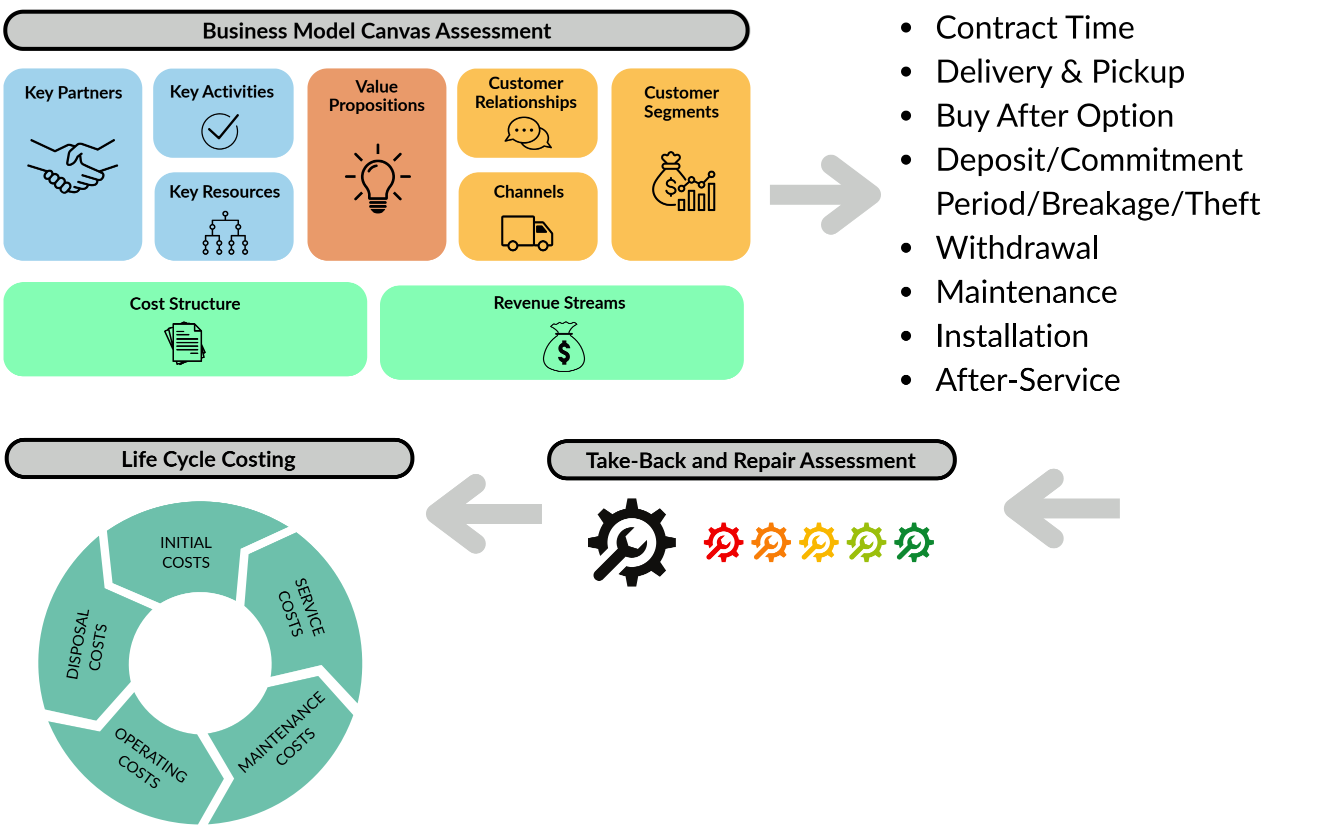


Figure 17. Developing circular business model (adopted from Hildago-Crespo et al., 2024)

Integrating product take-back and remanufacturing capacities is crucial, as are mechanisms for product health assessment, safe storage and efficient transport. This will help prevent damage that would reduce remanufacturing potential. The study indicates that most current systems lack comprehensive planning at these stages, resulting in missed opportunities for value recovery. Studies conducted within the Scandere project demonstrate that, for successful remanufacturing within PaaS, companies should focus on the following actions:

- **Define entry points for the take-back system**, considering both centralised and decentralised options, such as e-commerce returns or brick-and-mortar collection points.
- **Conduct a pre-assessment of product condition ("state-of-health") to avoid unnecessary transportation**. Products that are only fit for recycling should be routed directly to recyclers.
- **Implement cost-effective and environmentally sustainable transportation**, minimising the carbon footprint and avoiding unnecessary logistics operations.
- **Ensure secure and appropriate storage** of returned products to prevent damage and reduce environmental impact.
- **Carry out visual inspections of returned products** and make decisions on value-retention processes (VRPs)—such as reuse, repair, or remanufacturing—based on product condition.
- **Maintain quality control** and repacking standards to prepare items for the next service cycle.
- **Coordinate redistribution** or transportation of products for their next PaaS lifecycle, ensuring operational efficiency.

Compared to traditional linear sales, adopting subscription or pay-per-use models can increase the volume and complexity of logistics. Therefore, it is essential that companies proactively assess and optimise their take-back and logistics operations, covering areas such as customer collection, transportation to repair facilities and storage between contracts. To support this process, businesses are encouraged to use the Relog matrix (see Figure 18) as a practical tool when designing PaaS models. This matrix uses a traffic light system to help identify gaps in processes:

- Red (L) – Low resource availability
- Yellow (M) – Medium resource availability
- Green (H) – High resource availability

Where red or yellow areas are identified, it indicates a need to involve new (N) or existing (E) partners in the iterative development of the take-back system. This collaborative approach enables companies to strengthen weak areas and continuously improve their circular logistics capabilities.

Processes	PaaS provider Resources & Know-how			Process	
	L	M	H	E	N
Planning of collection from customer				√/✗	√/✗
Visual pre-assessment				√/✗	√/✗
Sorting at collection				√/✗	√/✗
Packing at collection				√/✗	√/✗
First mile-transportation				√/✗	√/✗
Storage of used products				√/✗	√/✗
Visual inspection & checklists for VRPs				√/✗	√/✗
Repair and servicing				√/✗	√/✗
Quality check & repacking				√/✗	√/✗
Last-mile transportation				√/✗	√/✗

Figure 18. Relog matrix

Adopting PaaS may result in temporary dips in profitability due to the company's absorption of responsibilities that were typically transferred to the consumer. Life Cycle Costing (LCC) is a vital tool in mitigating these issues. It is a valuable tool for evaluating the economic performance of service-based models over time, providing insights into potential cash flow challenges and informing strategic decisions regarding model configurations and pricing.

By investing in capacity assessment, redesigning business models, strengthening reverse logistics, applying financial foresight through LCC, and fostering strategic partnerships, companies can unlock the full potential of remanufacturing in PaaS. In doing so, they will be able to contribute meaningfully to circular economy goals.

Furthermore, organisational capacities can be enhanced through the exploration of new technologies that improve remanufacturing processes within PaaS models. Examples of notable technological solutions are presented in Table 8 below.

Table 8. Smart technologies in the remanufacturing process

SMART technologies to support the remanufacturing of used products		
Process	**Technology**	**Description**
Collection & transport	**Management System Transport Management System (TMS) with AI**	TMS systems using artificial intelligence optimise product collection and return routes, minimising transport costs and delivery times. By analysing data in real time, the system can dynamically adjust logistics plans, taking into account variable factors such as traffic volumes, weather conditions or vehicle availability.
	Blockchain	Blockchain technology provides an immutable record of all transactions and logistical steps involved in returning products. Thanks to this, it enables full transparency, reduced fraud and improved audit and compliance processes.
	Smart Inventory Management Systems (Inventory Management Systems)	Inventory management systems using IoT and AI monitor the volume of returned products in real time, predicting future returns and optimising storage and transport. This allows for better planning and minimisation of storage costs.
Quality assessment - inspection	**Machine Learning Vision Systems**	Advanced camera systems combined with machine learning algorithms enable automated inspection of returned products. This technology allows damage, wear and tear or other effects to be detected with high precision, speeding up the assessment process quality and minimises human error.
	Ultrasonic sensors for damage detection	The ultrasonic sensor is used for non-destructive inspection, detecting emitted ultrasonic waves reflecting off the workpiece. The waves reflect off porosity and other irregularities, as well as the underside of the workpiece. From the detected waves, the sensor can determine the type of defect, such as undercutting, cracks, porosity and other irregularities. It can also determine the size, shape and location.
	Thermal Emission Analysis Systems Imaging Analysis Systems	Thermal imaging cameras monitor component temperatures during inspections, detecting overheating, damage or malfunction of electronic components. This allows early detection of potential quality problems.
Dismantling	**Automated Robotics Dismantling**	Robots equipped with advanced manipulators and sensors enable the precise disassembly of products into component parts. Automating this process increases efficiency, reduces the risk of component damage and speeds up the entire remanufacturing process.
	VR technologies to Operator Training Dismantling	Virtual reality (VR) is used to train operators in the efficient and safe disassembly of different types of products. This allows for realistic simulations without the risk of damage to actual components.
	Automatic Systems Automated Sorting Systems	These systems automatically classify and segregate parts during disassembly, increasing the speed and accuracy of the process and minimising human error.
Reprocessing	**Rapid Manufacturing – rapid production**	A manufacturing technology that uses incremental methods to directly produce finished products or their components, bypassing traditional manufacturing steps such as the creation of moulds or tools. Techniques used: partly FDM, especially SLS, SLM and EBM, as well as the machining of engineering plastics and metal alloys on CNC machine tools.
	3D printing	3D printing (additive manufacturing) is the process of producing physical three-dimensional objects based on a CAD or digital 3D model. Printers can automatically optimise the production process of components by adjusting the print parameters over time depending the materials and quality requirements.
Reassembly	**Assembly lines with IoT (Internet of Things)**	Assembly lines equipped with IoT devices can monitor and optimise the process in real time, adjusting the variable to the specific parameters of the equipment to be installed.
	Cobots (Collaborative Robots)	Cobots working with assembly line workers, supported by augmented reality (AR) technologies, enable the precise and rapid assembly of components. AR provides workers with visual cues and instructions in real time, increasing the accuracy and reduces the time needed for training.
	Automated Parts Tracking Systems Systems	These systems use RFID and IoT to locate each unit in the assembly process, providing full control over resources and minimising the risk of shortages or assembly errors.
Final qualitative assessment	**Big Data analysis**	The use of Big Data technology to analyse large data sets generated from different stages of production makes it possible to identify trends and patterns affecting the final quality of the product.
	Digital Twin and Simulations	Digital Twin technology creates virtual replicas of final quality of products which can be simulated and tested for various quality parameters. Combined with AI algorithms, this enables an accurate assessment of the final quality of products before they are re-sold, ensuring compliance with high standards.

Despite growing interest in circular economy models, there remains a significant gap between isolated pilot initiatives and the widespread adoption of remanufacturing as a mainstream practice for products such as household appliances. The academic literature to date offers limited, fragmented insights, and industry uptake has been slow. To address this, Rem-Cap-Up guides practitioners through the complex landscape of circular transformation with a focus on CRM recovery. To provide practical assistance to Original Equipment Manufacturers (OEMs) and other relevant parties seeking to implement PaaS-based remanufacturing on a large scale the findings are sum up in Figure 19 (below).

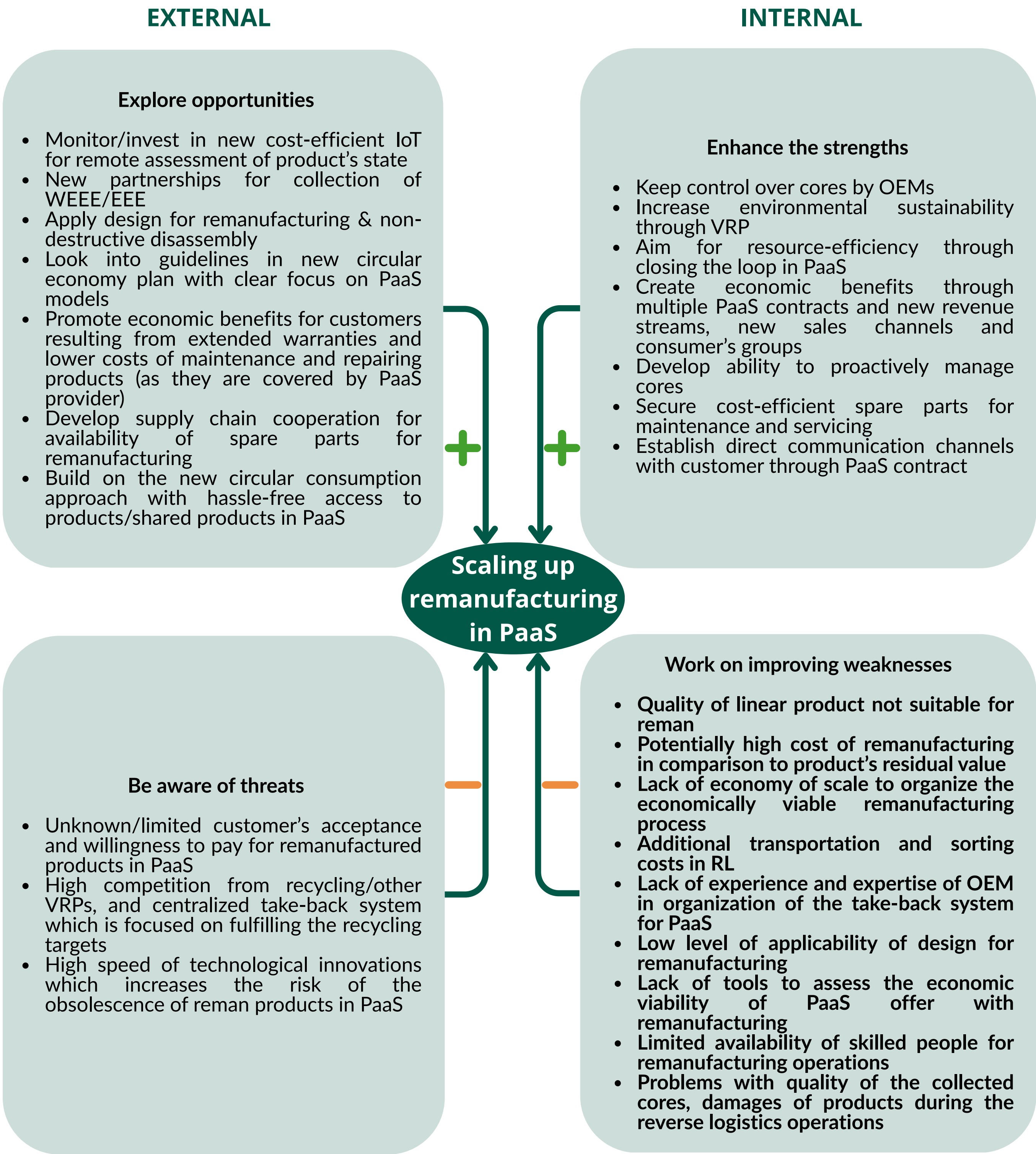


Figure 19. Decsion-making aid to support the scaling up remanufacturing in PaaS

Rem-Cap-Up is an innovative capacity-building model designed to help companies increase their remanufacturing capacity within Product-as-a-Service (PaaS) business models, particularly for electrical and electronic equipment (EEE) in the consumer (B2C) market. Although the Rem-Cap-Up model was developed with a strong focus on EEE under the EU's WEEE Directive, it can be adapted to other industries and regulatory environments with contextual adjustments. The scalability of the model to other sectors is considered feasible, pending an assessment of compatibility between challenges and enablers.

The Rem-Cap-Up model provides a practical framework for identifying and addressing remanufacturing capability gaps within PaaS models for EEE in consumer markets. It supports targeted capacity development by guiding practitioners through a structured assessment of technological, organisational, and market factors. Crucially, the model also promotes a transition from conventional recycling, which is frequently suboptimal for recovering critical raw materials, to more resource-efficient solutions that maintain the circulation of CRMs. This enables more effective circular strategies and accelerates the transition to circular business models.

ACKNOWLEDGEMENTS

This study received support from the SCANDERE project (Scaling up a circular economy business model by new design, leaner remanufacturing, and automated material recycling technologies), which was granted by the ERA-MIN3 program under grant number 101003575. Poznan University of Technology was financially supported by NCBR, National Centre for Research and Development, Poland (No. ERA-MIN3/1/SCANDERE/4/2022).

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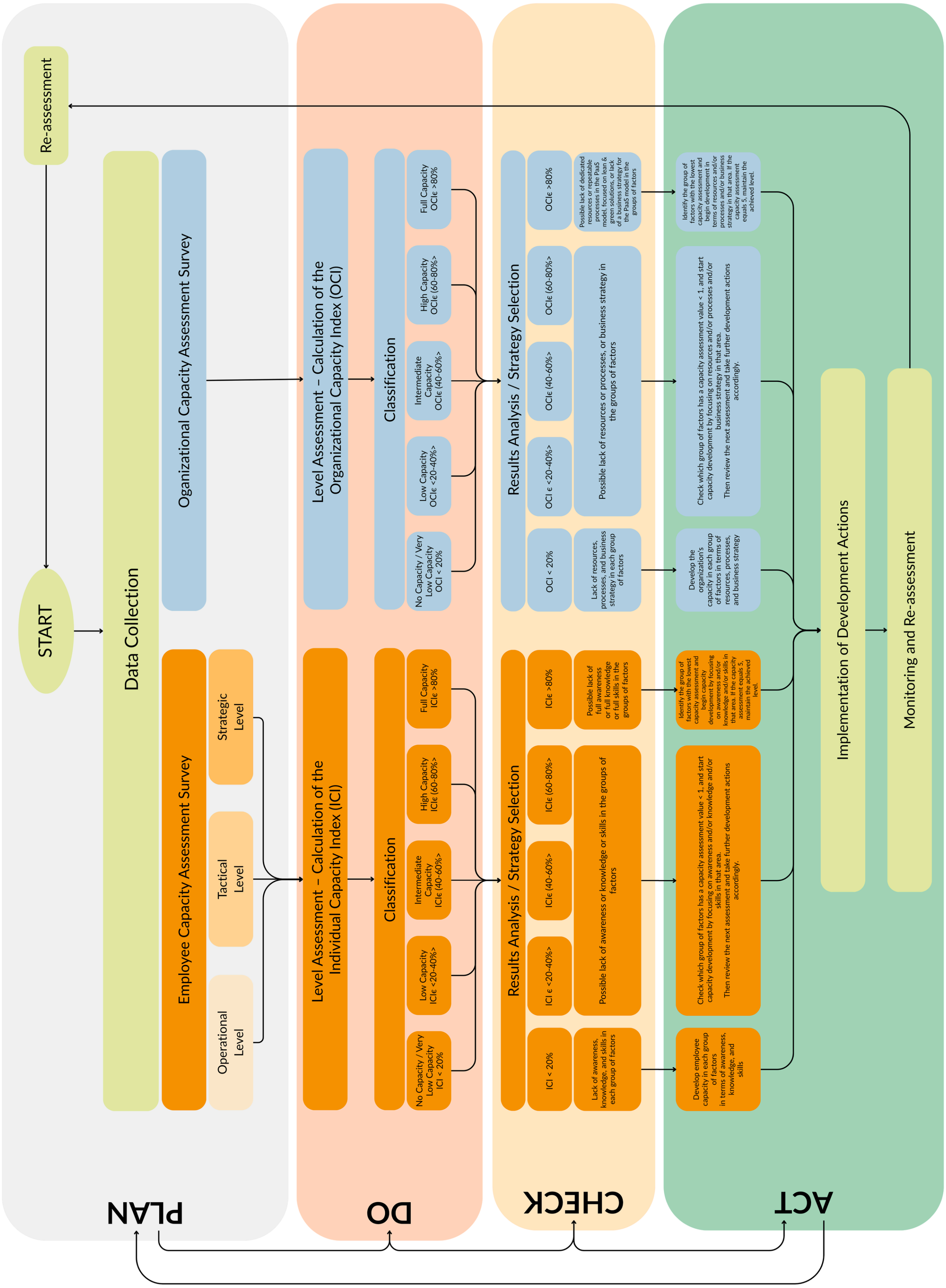
APPENDIX



PLAN
DO
CHECK
ACT
START
Re-assessment
Data Collection
Oganizational Capacity Assessment Survey
Employee Capacity Assessment Survey
Strategic Level
Tactical Level
Operational Level
Level Assessment – Calculation of the Organizational Capacity Index (OCI)
Level Assessment – Calculation of the Individual Capacity Index (ICI)
Classification
Full Capacity OCIϵ >80%
High Capacity OCIϵ (60-80%>
Intermediate Capacity OCIϵ (40-60%>
Low Capacity OCIϵ <20-40%>
No Capacity / Very Low Capacity OCI < 20%
Full Capacity ICIϵ >80%
High Capacity ICIϵ (60-80%>
Intermediate Capacity ICIϵ (40-60%>
Low Capacity ICIϵ <20-40%>
No Capacity / Very Low Capacity ICI < 20%
Results Analysis / Strategy Selection
Possible lack of resources or processes, or business strategy in the groups of factors
Lack of resources, processes, and business strategy in each group of factors
Possible lack of awareness or knowledge or skills in the groups of factors
Lack of awareness, knowledge, and skills in each group of factors
Possible lack of full awareness or full knowledge or full skills in the groups of factors
Check which group of factors has a capacity assessment value < 1, and start capacity development by focusing on resources and/or processes and/or business strategy in that area. Then review the next assessment and take further development actions accordingly.
Develop the organization's capacity in each group of factors in terms of resources, processes, and business strategy
Develop employee capacity in each group of factors in terms of awareness, knowledge, and skills
Implementation of Development Actions
Monitoring and Re-assessment