Technical report of the project Scandere

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

Part of Deliverable 0.9

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Authored by Scandere partners
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1. Introduction

Product-as-a-service (PaaS) can be seen as a business model, where a provider keeps the ownership of the products and gets paid for giving end users access to the products. PaaS will solve the problem of product collection after end-of-use for increasing the efficiency of resources including critical raw materials (CRMs), as the products are returned to the provider as part of the contract and thus handled in professional manners and with their information in the previous phases of their lifecycle. Also, PaaS incentivizes the provider to use the product with its fuller technical lifetime, resulting in increased efficiency of using CRMs. In Europe, PaaS offerings are found in various markets, including household goods. However, they currently form a niche market, providing a potential for development. Therefore, the Scandere project was executed aiming to demonstrate PaaS offerings with household goods and develop scientific knowledge. It covered various areas (ERA-MIN3 topics 2, 3, 4, and 5.1) along the product lifecycle as depicted in Figure 1. This technical report highlights project results.

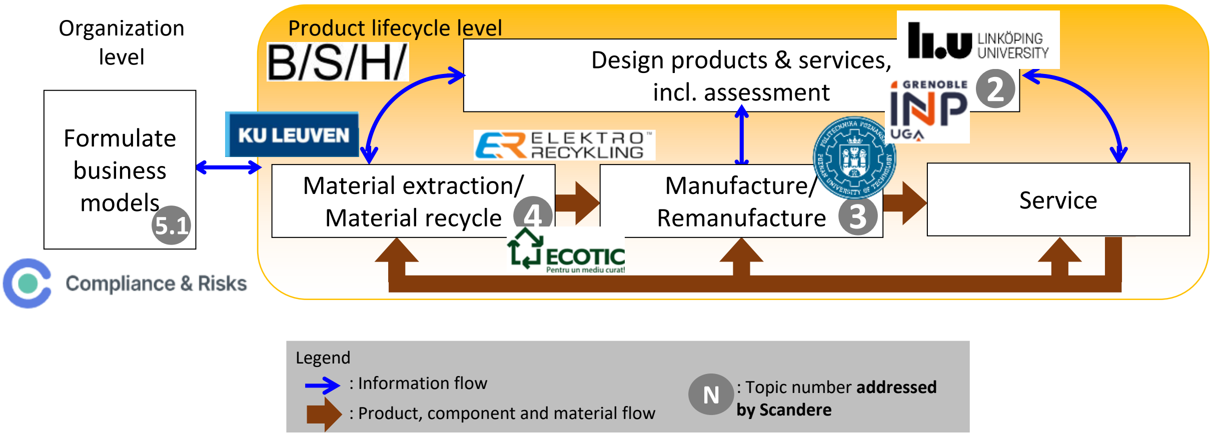


Figure 1. Areas covered by the partners in the Scandere project along the product lifecycle

List of abbreviations

B2B ....business to business
B2C ....business to consumers
CE ....circular economy
CEAP ....circular economy action plan
CRM........critical raw material
CRMA .....critical raw materials act
e-DIM .....ease of disassembly metric
EEE ....electrical and electronic equipment
EoL..........end-of-life
EU...........European Union
KER ....key exploitable result
LCA ....lifecycle assessment
LCC ....lifecycle costing
LDA.........Large Domestic Appliance
MFA........Material flow analysis
OEM ....original equipment manufacturer
PaaS........product-as-a-service
PCB ....printed circuit board
Re-DiM ...Robotic Ease of Disassembly Metric
SDA.........Small Domestic Appliance
SoH ....State of Health
S-LCA ......Social life cycle assessment
TCO.........Total cost of ownership
TRL..........technology readiness level
WEEE ......waste from electrical and electronic equipment
WP..........Work Package

2. PaaS business development through demonstration

Main authors: BSH Hausgeräte GmbH, Linköpings Universitet, and Katholieke Universiteit Leuven.

Challenges to CRM efficiency of household goods in Europe

PaaS offerings with electrical and electronic equipment (EEE) are increasingly launched on the European markets. A scientific review of extant research [1] informs that integrating products and services is important to increasing environmental performance, e.g., planning the maintenance frequency simultaneously in deciding component durability. However, whether such knowledge has been exploited in practice is largely masked. Furthermore, all PaaS offerings on the markets are not necessarily designed or practiced with better environmental performance. Therefore, a major knowledge gap at the industrial-application level concerns how existing scientific knowledge could be applied to develop a PaaS offering in practice for improving sustainability performance (economic, environmental, and social).

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 1.1 – Analysing science-based solutions, Task 1.2 – Developing and deploying products and services for three PaaS offerings, and Task 1.3 – Analysing learning outcomes in WP1 – Developing PaaS offerings.

The project aimed to develop and deploy products and services for three PaaS offerings with home appliances in European markets through practitioners' application of compiled scientific knowledge to the three cases. It also analysed learning outcomes from the existing research and innovation.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

Existing scientific insights were collected to form a collection of solution elements as a starting point. According to a scientific literature review on developing PaaS offerings [1], one of the five challenges for decision making in PaaS design is to choose and design the right business model. Hence, business model aspects were investigated in detail. Business cases were also collected from the scientific literature and complemented by grey literature with special attention to EEE and related product categories such as home appliances, gardening tools, and electric scooters/bikes.

Based on the collected information, the PaaS with a battery-driven vacuum cleaner was developed and demonstrated by a Scandere partner, BSH. The vacuum cleaner is shown in Figure 2.

Figure 2. Vacuum cleaner used in the demonstration (Source: https://www.bluemovement.com/nl-en/plans/vacuum-cleaners/q8a0033888)

First, several possible types of PaaS business models were identified after analysing extant scientific knowledge. A general business model canvas has been used. Personas [2] (related to customer segments) were used, and anticipated customer characteristics have been identified. Different design implications were analysed for each type of business model. Building upon these three types, two promising offerings have been identified: an offering of a vacuum cleaner with a pay-per-month subscription (PaaS) and an offering of only the battery as a pay-per-month subscription (Battery-as-a-Service), with the vacuum cleaner offered separately in the normal one-off sales business model. For the Battery-as-a-Service offering, the volume of batteries is key for business viability. Hence, incentivised large-scale collection of Bosch batteries was researched in addition [3]. Two hypothetical battery collection methods, i.e., incentivized returns and waste sorting, were examined with Monte Carlo simulations. While waste sorting was found more cost-effective, incentivized returns yielded higher-quality cells, enhancing CRM recovery. State of Health (SoH) testing will ensure the precise classification of extracted cells, maximizing CRM retention through reuse in remanufactured battery packs or secondary applications.

These two offerings were further elaborated on with the business model canvas. BSH has deployed the PaaS offerings of vacuum cleaners with a pay-per-month subscription on the Dutch and German markets. These PaaS offerings are a product of investigation based on scientific knowledge. The PaaS offerings on the market demonstrate the viability of the battery-driven vacuum cleaner PaaS offerings.

The second PaaS demonstrated is for home appliances, such as washing machines (see Figure 3), provided by a collaboration between BSH and a social enterprise in Belgium called SAAMO West-Vlaanderen (SAAMO, hereafter). The project investigated the PaaS, especially from the social sustainability perspective. This variant of the PaaS model under the name Papillon targets families living in poverty who cannot afford to buy energy-efficient household appliances [4]. SAAMO's mission is to help socially vulnerable people. The guideline for social life cycle assessment (S-LCA) provided by UNEP/SETAC was used [5] [6]. Among the 41 subcategories, many were assessed as having no influence or unknown, and none was assessed as net detrimental; however, the five subcategories of community engagement, promoting social responsibility, end-of-life responsibility, poverty alleviation, and health issues for children as consumers were assessed as (possibly) net beneficial.

Figure 3. Washing machine used for the PaaS in Papillon (Source: https://papillon.saamo.be/nl/ *)*

The third PaaS offering targeted was robotic lawn mowers in European markets. A financial assessment model was developed to support the transformation of original equipment manufacturers (OEMs) to PaaS business models [7]. This model was applied to the life cycle costing (LCC) of a robotic lawn mower, providing insights into the profitability and feasibility of the transformation. When transforming from traditional one-off sales towards PaaS, there is a shift of cost burden from the user to the provider and vice versa, meaning that the value of the business model setup also shifts. With the support of the model (ibid), the robotic lawn mower provider was able to estimate the remanufacturing and refurbishment costs using historical data on repair and maintenance, as well as assess the financial performance of PaaS with a bottom-up-based LCC approach.

Achievement/findings regarding the inter-dependent activities

A main concern for the end users is the total cost of ownership (TCO). In a traditional product one-off sales offering, the user would bear the cost of purchasing the product outright and cover the expenses related to the product usage, such as maintenance and repairs. However, under PaaS, these responsibilities are shifted to the provider. The user avoids significant upfront costs and can benefit from predictable regular payments over the use phase. The TCO is primarily based on the PaaS fee in this setting (i.e., the regular payments). If the provider can reduce the total life cycle costs, it implies that a lower PaaS fee can be offered to its customers, which could trigger a higher level of engagement. This can be realized by using more durable products/components that result in lower maintenance costs as a design choice. The calculation model showed that this relationship between the provider and user is critical to get right; otherwise, at least from a cost perspective, the user can view the PaaS as less financially attractive than traditional one-off sales, causing poor profitability of PaaS and negating its environmental benefits.

Future research and innovation needed

After carrying out the project, it was found that business practice needs to incorporate more than the product lifecycle issues. The PaaS provider needs to collaborate with suppliers of components, each of which has its own lifecycle, and reverse logistics providers. This finding is in line with the recently proposed double systems perspective [8], including a product lifecycle and a value cocreation ecosystem. Future research and innovation need investigation with more complex systems. The social aspect is more underexplored than the environmental and financial aspects. The applicability of available guidelines needs to be investigated further and more industrial cases need to be documented to advance the area in line with a recommendation from a systematic literature review by [9].

3. Regulations related to PaaS and circular business models

Main author: Compliance and risks.

Challenges to CRM efficiency of household goods in Europe

From the seven interviews we conducted, it became clear that most companies were waiting to see whether a PaaS model could be profitable before committing resources to large-scale consumer-level programs.

- PaaS models have been implemented in business to business (B2B) settings for high-cost, limited-use equipment such as construction and medical diagnostic equipment. This implementation is purely for financial reasons with little or no sustainability function since these high-value products are unlikely to be discarded as waste.
- PaaS for business to consumers (B2C) markets have a greater potential impact on sustainability but experience more barriers to deployment and profitability than B2B markets.
- Uncertainty is the dominant factor. None of the respondents had a clear picture of the regulatory framework applicable to PaaS models with regard to finance, product safety, labelling, or advertising.

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 2.1 – Surveying experience in practicing PaaS in the EU, Task 2.2 – Investigating existing regulations in the EU, and Task 2.3 – Deriving recommendations for European regulations for PaaS in WP2 – Assessing European regulations for PaaS. Our expectation was that PaaS would help to ensure access to CRMs because products containing the minerals and materials would remain under the control of the product manufacturers.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

In the interviews with industry, we only found one respondent in the strictly B2C realm of consumer products: a small pilot-project company with 20 employees set up by a larger manufacturer. Due to its small size, this company had no compliance officer and had no special way to recover CRM itself or provide CRM for use by the manufacturer. We found no PaaS in B2B markets that would directly recycle or reuse CRM.

Our small sample of PaaS providers and relevant regulations produces two points of departure for regulatory recommendations.

- Existing PaaS programs related to consumer products are too small at present to contribute meaningfully to the circularity of the businesses in which they operate or the economy overall.
- There is a disconnect between the existing regulations and CRM efficiency. PaaS programs cannot contribute to compliance with existing waste, ecodesign, or sustainability regulations because these regulations focus on linear consumption and provide no incentives for PaaS.

Achievement/findings regarding inter-dependent activities

We found that the regulatory focus has, over the past decade, drifted away from concrete infrastructure development and into data management with no physical benefits. One example of this is a recent Swedish proposal that intends to clarify liability but does not take into account the cost to consumers or the reality of market enforcement [10]. To the extent that it clarifies who is responsible, it fails to address the fact that any regulatory determination of responsibility will undermine the private contracts required for the practical implementation of the law. Likewise, it proposes unspecified improvements in infrastructure and enforcement without clearly establishing the source of funding for this. The memorandum recognises that non-compliance is a source of substantial profit but does not recognise that the solution will need to make up for that lost profit.

The project has found that local environmental regulations, high wages, and the high cost of property make local dismantling and sorting of waste products economically prohibitive, while the export of waste equipment to low-income regions with few environmental protections and minimal law enforcement virtually guarantees the loss of circularity. The updated EU Batteries Regulation [11] consolidates the diffuse, local requirements into a more coherent legal corpus but does not illuminate who or what body will provide the real estate, infrastructure, logistics, and labour required to realise the stated goals of resource recovery. The only thing that is clear is that labels, documents, and reports will multiply, adding to the scourge of the 21st-Century information economy: an orgy of data with a paucity of ideas.

As the results fail to materialise, regulatory goals and assessments have become more recursive and self-referential. The German parliament has proposed an amendment to the e-waste law to substantially increase the collection of e-waste from households and remove flammable lithium batteries [12]. The cost to the economy is projected to be approximately EUR 2 million annually, but this "is to be fully offset by the planned savings from the law to adapt battery law" in accordance with the new Batteries Regulation. Meanwhile, that law is projected to relieve the economy of EUR 12 million in compliance costs [13]. This relief will come from the "other costs" category that states: "To the extent that additional costs with an impact on individual prices arise in connection with the Adaptation Act, these additional costs are essentially based directly on Regulation (EU) 2023/1542 itself. Reference is made to the EU Commission's impact assessment". In other words, the savings will come from the fact that costs that had been attributable to German law are now attributable to EU law.

Turning to the EU law, there is no overall assessment of the cost to the economy in the EU impact assessment for the new batteries regulation [14]. The EU estimates that the cost of collection would be "around EUR 1.09 and EUR 1.43 per capita per year, respectively, to be financed through the mechanism of Extended Producer Responsibility" (ibid.). However, the assessment does not pinpoint where the money will actually come from. "Producer Responsibility" could mean anyone in the supply chain, from component manufacturers to component assemblers, assembled product distributors, brand owners, importers, wholesalers, and retailers. However, we can expect consumers to ultimately pay higher prices for compliant products and lower prices for non-compliant products.

Our research has found ominous signs of a retrenchment of unsustainable business as usual. For example, the EU Commission [15] has quietly recognised that resource recovery and local production are insufficient to secure an adequate supply of critical raw materials, instead signing an agreement with Rwanda as well as agreements with other nations involved in the Congo region's ongoing violence, effectively abandoning the goals of the conflict minerals regulation. Crucially, the conflict minerals regulation is still in force, requiring corporations to perform due diligence on the sourcing of raw materials. The result is a database of boilerplate reports, predominantly from Chinese suppliers, all providing assurances that their minerals do not contribute to conflict in the region.

Future research and innovation needed

The next step towards managing CRMs through circular economy principles will depend on infrastructure, rather than information: at present, the economic infrastructure is linear and dispersive. Without improvements in collection, transportation, and processing facilities, it will be physically impossible for the economy to become more circular. Developing the economic infrastructures relies on governmental investments and is a part of business model issues in a broader sense (including private and public parties). As mentioned in our finding above, PaaS programs cannot, at present, contribute to compliance with existing waste, ecodesign, or sustainability regulations. The American Chamber of Commerce illustrates the fundamental problem in a comment on the Albanian Extended Producer Responsibility law [16]:

> As it stands now, the new product tax will simply add an additional financial burden on taxpayers and will have little or no impact on improving environmental aspects. Businesses that do not have any credible alternative, as we will detail below, will be willing to pay the tax and will not engage seriously or at all in addressing the environmental problems that this Draft Law aims to address... In fact, the Draft Law stipulates in several other articles, cooperation with local government authorities and licensed operators, but fails to define or demonstrate a credible scheme for the collection, management and treatment of waste.

In other words, these regulations are structured so that the most efficient way to comply is to treat them as a tax, which will be paid by high-profile producers and flouted by producers whose margins are too thin. This comment reveals why the gap between the regulation and practical implementation cannot be closed by additional regulation or strict enforcement. The methodology is misaligned with the reality. The result of the present method of sustainability regulation is that people are paying more and polluting more. Put another way, western societies are willing to pay extra for the privilege of living unsustainably. Service-based business models will be better facilitated by regulations that promote effective infrastructure and cooperation rather than more extensive use of the existing product stewardship obligations. Future research will be needed to determine what kinds of infrastructure will best support sustainable business models.

4. Sustainability assessment of PaaS

Main author: Linköpings Universitet.

Challenges to CRM efficiency of household goods in Europe

With PaaS models, a provider is incentivized to increase the efficiency of using natural resources, including CRMs. Economically, the potential is found to create and capture higher value with PaaS models than the product one-off sales through monetizing, e.g., increased availability and hassle-free operation. However, the economic consequences of PaaS are less documented than the environmental effects [17], and the social dimension of sustainability is even less researched [18]. The industry lacks support for addressing and improving the three sustainability pillars of PaaS models.

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 3.1 – Performing lifecycle costing, Task 3.2 – Analysing social and environmental aspects, and Task 3.3 – Generalizing learning outcomes from industrial cases in WP1 in WP3 – Assessing the sustainability of PaaS offerings.

The project planned to perform lifecycle costing (LCC) [19], aiming to create a greater understanding of how the PaaS economic potential (exemplified above) could materialize in better life cycle costs from the provider's and the user's standpoints. Social life cycle assessment (S-LCA) [5, 6] on PaaS offerings with household goods on European markets was also planned.

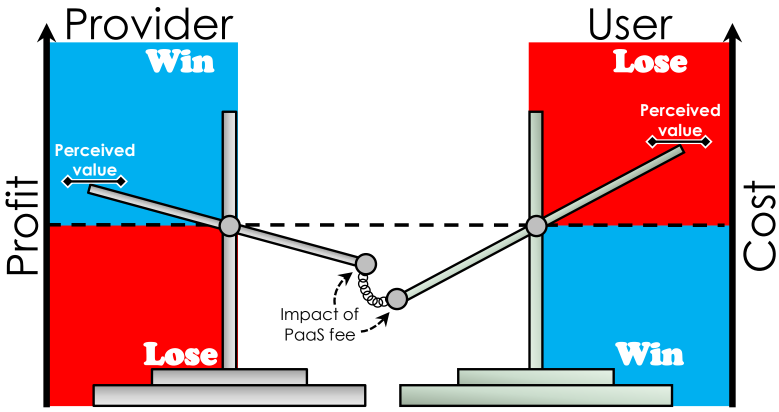
PaaS' contributions to CRM efficiency; achieved/found in Scandere

By carrying out multiple LCC case studies on PaaS with household goods in European markets, a generic understanding was obtained as follows: Major factors determining the economic aspect of PaaS are the PaaS fee, contract length, logistics, services (including maintenance, repair, and refurbishment), production, and back-office activities. The PaaS fee can be set according to the perceived value of PaaS subscribers, which includes hassle-free operation. A systematic assessment approach consisting of three steps with modelling logic and mathematical formulae was developed [20]: 1) provide a cost overview for each business model, 2) create scenarios by modifying the cost drivers, and 3) combine scenarios to reach synergetic effects.It is generally recommended that a PaaS provider consider, among others, two factors: the back office and the services. The back-office activities supporting PaaS are needed and are additional unless the provider is dedicated to PaaS provision. In particular, when an OEM executes PaaS on a small scale, the back office supports the one-off sales business, too, and this double burden is a challenge to overcome. One way to reduce the back-office cost was identified: employing a third party, such as a retailer in the case of robotic lawn mowers; however, the OEM must be aware of the downsides, such as less contact with users and lost opportunities for accumulating knowledge [21]. Regarding the services, maintenance is also performed when an end user owns the product, and the end user bears the effort in the one-off sales. In the case of private end users, the maintenance effort may not be impactful to the same extent as professional users because many end users do not translate the maintenance effort into monetary terms in the same way businesses do.

The mathematical formulae showed that a complex relationship between the provider and user is critical to get right, otherwise, at least from a cost perspective, the user can view the PaaS as less financially attractive than traditional one-off sales, causing poor profitability of PaaS and prevents its environmental benefits. This relationship is depicted in Figure 4 as the PaaS libra.

S-LCA was performed for a specific PaaS in Belgium with home appliances, such as washing machines provided by an original equipment manufacturer (OEM), targeting impoverished families who cannot afford energy-efficient household appliances. The results shed light on multiple positive aspects and a possibly negative one [22]. The factors that caused the positive assessment are twofold. Firstly, the constellation, including the social enterprise whose missions include supporting socially vulnerable people, makes this business viable. Secondly, the PaaS contract enables affordable monthly fixed payments without a high upfront payment that would be necessary if the same product is purchased. On the other hand, the PaaS inherently necessitates the OEM to be engaged more in providing services, possibly affecting working hours.

Material flow analysis (MFA) was performed [23] according to the increased interest in CRM efficiency (e.g., the EU CRM Act issued in 2022), though it was not originally planned. An account was made for PaaS in terms of the CRM efficiency of a battery-driven vacuum cleaner in European markets (e.g., Co, Ni, and Li). The product one-off sales model and the PaaS model were compared, where the resource efficiency of all the investigated CRMs shows that the PaaS model outperforms the sales model by approximately 3% to 50% for the inflow (the ratio depends on the material and component). The outflow from the PaaS is also superior regarding landfilled and recycled materials. The mechanisms behind the superiority of PaaS are documented as prolonged component lifetime and better component salvage/harvest by industrial control.



Note: The weight of the PaaS fee shifts the balance relative to the perceived value for both provider and user, moving the perceived value into either the win or lose area. The provider can always increase the PaaS fee to cover costs, but this triggers a linked counterreaction in the user's perceived value. A balance is necessary to achieve a win-win state from both perspectives, meaning the provider must minimise its costs to offer a product under a PaaS fee that is reasonable for the user.

Figure 4. The PaaS libra

Is there any difference between the plan and the achievement/findings? Why?

The assessment of PaaS offerings from the economic, social, and environmental perspectives was found to be more complex than one-off sales because the PaaS provider tends to incorporate the longer time horizon (along the product lifecycle) and the larger part of the value network (or the business ecosystem) involving higher uncertainty as described as a double systems perspective [8] shown in Figure 5. Due to this complexity, the LCC analysis investigated where, in a multi-dimensional space (in a mathematical sense), win-win situations exist (for the provider and the end user), which required more resources than planned. S-LCA revealed the need to address a highly broad range of topics (e.g., from safety/health and community engagement to poverty alleviation) that PaaS could potentially affect. The MFA results highlighted the complexity of analysing a PaaS where the product components with differing technical lifetimes benefit from their suitable treatment, such as reuse, remanufacturing, and recycling.

Achievement/findings regarding the interdependent activities

The complexity stated above is often caused by interdependent activities. One concrete example from the LCC study showed that a combination of longer PaaS contract lengths and lower maintenance costs could provide a win-win state if sufficiently high product durability is implemented [20]. Another example from the MFA of the vacuum cleaner was that both reuse and part recovery rates depend on the possibility of efficiently disassembling the product (determined by product design) [23].

Future research and innovation needed

Future research and innovation are needed regarding applying a PaaS model to other product categories and further generalizing the obtained knowledge, as well as advancing MFA to identify which decision making creates a higher impact on the CRM efficiency and, based on that, investigating return on investment of various alternatives. Carrying out S-LCA with more cases and in more depth is also required; the deeper study might require a narrower scope.

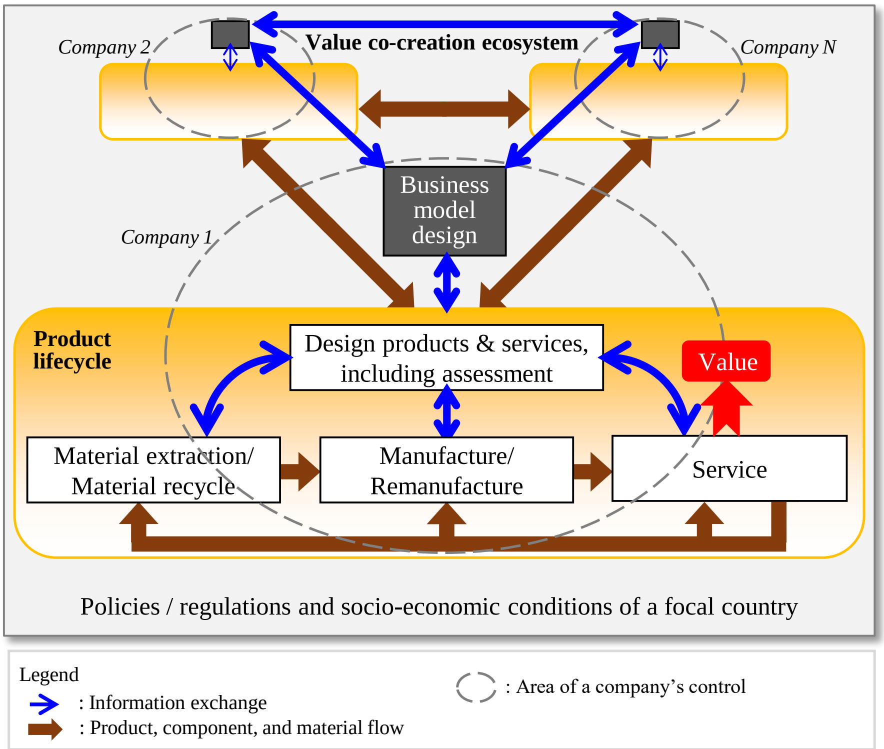


Figure 5. The double systems perspective [8]

5. Designing PaaS

Main author: Institut Polytechnique de Grenoble.

Challenges to CRM efficiency of household goods in Europe

Like white goods, EEE typically contains conventional metals and critical raw materials (CRMs) in various composite forms. Current recycling methods are highly challenged in recovering the CRMs found in EEE due to their low concentrations [24]. This underpins the need for design methods that support keeping the entire product and/or its components in circulation as long as sensible through other circular strategies like reuse, repair, refurbishing, remanufacturing, and repurposing. These circular processes, however, need to be facilitated through the very product design (modular design, design for disassembly, etc.) as well as through the co-design of the product with the circular business model, and the data and information flows that are required to keep the product and its components circulating. This WP has dealt with the establishment of a design approach that focusses on exactly these aspects and its deployment in the form of a configurable design platform.

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 4.1 – Formulating research issues based on challenges in industrial use cases, Task 4.2 – Developing a design method, Task 4.3 – Applying the method to cases, and Task 4.4 - Generalizing learning outcomes on design from industrial cases in WP1 in WP4 – Design research for PaaS.

As of the Scandere proposal, the project planned to analyse and make explicit research issues linked with PaaS, mostly based on industry surveys (Task 4.1). Driven by the use cases provided by the industrial partners, the project planned the development (Task 4.2) and application (Task 4.3) of a design methodology that provides support and guidance to designers of products, services, and processes to integrate CRM efficiency considerations in the design in a systematic manner. The proposal also envisaged the provision of access to the proposed methodology in the form of a tooling, signified as a design platform. Finally, Task 4.4 planned to generalize the insights and learnings gained from work on the specific industrial use cases that formed the backbone of this project.

As per the needs and wants for the project by one of the lead companies providing the use case (BSH), we focussed on redesigning the business model around the existing product rather than directly tapping into the product design improvements. Our pilot company partners aimed at validating PaaS Business Models before investing in redesigning products and the implied re-configuration of production environments and supply chains. We believe that their situation and priorities can be considered representative for many other industries and companies: the attractiveness of PaaS with respect to other forms of PSS tends to shed light on other elements than the product itself before transitioning from a linear model to a circular one.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

The approach to responding to the Task 4.1 objective was an in-depth literature study, even supported by AI tools, to assure a broad and deep coverage of the highly interdisciplinary research area of PSS, and more specifically, PaaS. The project complemented this with a thorough literature study with grounded field input from industry. For the latter, direct input from the industrial consortium partners was predominant. In addition, each academic partner mobilized its industry network to harvest and integrate the practical perspective in Scandere research articles and deliverables. Regarding industrial use cases, with respect to design challenges, solutions, and key performance indicators, the project focussed on EEE. The specific BSH use case of household washing machines and vacuum cleaners provided guidance and a playing field for validating research hypotheses.

Among the key insights about what PaaS can contribute to increasing CRM efficiency is the fact that the co-design of the PaaS' underlying products and services with the business model is pivotal [25]. The reasons for this are numerous; e.g., the design and deployment of a circular process requires new additional processes (e.g., reverse logistics and other circular processes), and partnerships, customer acceptance, economic viability, and cannibalization impact the existing linear offerings. At the centre of the PaaS value proposition, design methods shall be user-centric and address value-adding use experiences rather than mere product functions [1]. Moreover, design for disassembly and repairability are considered key facilitators for CRM efficiency through PaaS, as well as the latter's effectiveness and economic viability [26]. For these design considerations, many design methods and patterns can already be found and applied [27]. The challenge is making them available to designers in a form that supports and even guides them in the integrated design process with product and PaaS strategists (for covering the design aspects related to the business model) [28, 29].

In terms of establishing a PaaS design method, the project developed an intuitive yet holistic methodology fundamentally inspired by the stepwise approach of implementing circular business models in an organisational and process environment that has been shaped and practiced by product and process models widely in industry over the years. Its core architecture links a set of 169 design challenges with 229 design guidelines and 182 KPIs, which allows for measuring the PaaS design solution's environmental performance improvement [27]. The method proposes a selection mechanism, allowing it to reduce this huge PaaS design opportunity space to a size that is appropriate for a given design challenge, and with a focus on those parameters that are considered the most important.

The project applied this methodology to the BSH vacuum cleaner [28], as well as to electric circuit breakers, the latter in the context of a PhD work together with Schneider Electric (a non-project partner) [29]. Both application cases confirmed the usability and relevance of the proposed PaaS design method, even if – in both cases – it was not possible to actually redesign the products. The related tools (developed in MS Excel) are an important part of the PaaS design platform; see Figure 6. The latter's key originality is that it links Business Model Development Tools with Product and process Design Decision Guidelines and Tools, based on the Sustainability Validation Tools Life Cycle & Critical Raw Materials Assessment, Life Cycle Cost Assessment, and Social Life Cycle Assessment. Except for the Social LCA, all these platform tools have been successfully applied.

Any difference between the plan and the achievement/findings? Why?

The plan did not foresee the application of the Design Method and Platform to any product other than those proposed by the Scandere partners. In this regard, we have overfulfilled the work package's objectives.

Achievement/findings regarding the inter-dependent activities

There was a particularly intensive collaboration with WP3 since the ecological, cost, and social impact assessment methods have a strong influence on Design Choices guided by the PaaS Design Method and Platform.

Future research and innovation needed

This project and work package tackled numerous research challenges, which would have been difficult to address in another setting. In particular, the close collaboration of several domain experts in industrial cases was key to obtaining original results. On the other hand, the results achieved have also brought up the need for further research. Integrating the use of LCA, LCC, and S-LCA methods for guiding design choices is a particularly huge challenge since the research published thus far treats them all separately. Each circular process (reuse, repair, remanufacturing, recycling, etc.) requires specific consideration and modelling in both the Design and Assessment Tools Mixing circular processes, as appropriate in PaaS contexts. Moreover, simplifying the Design Method and the required tools in a way that they can be applied in an intuitive and efficient manner in industrial practice is also an area that still requires further investigation.

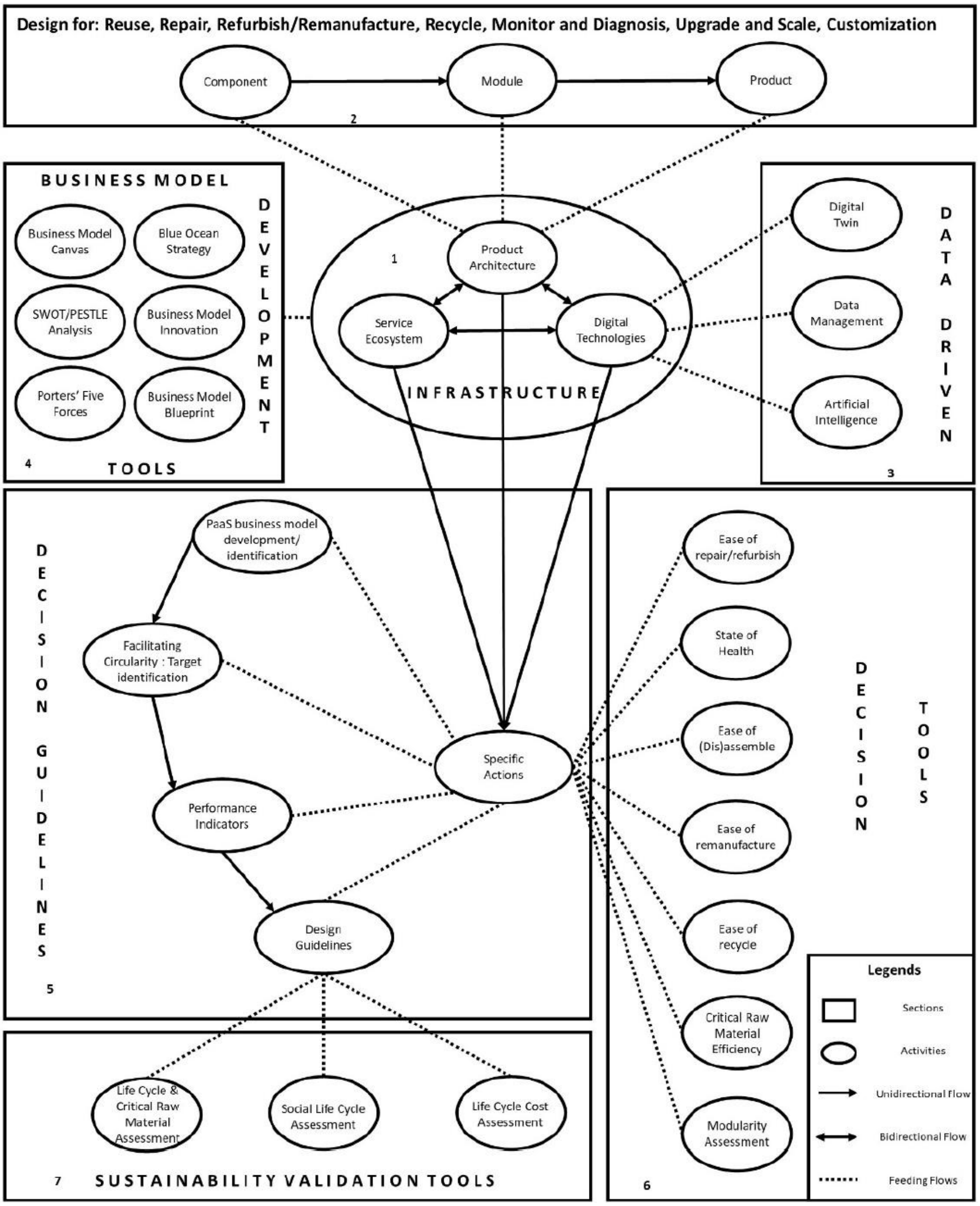


Figure 6. The blueprint for the PaaS design platform [25]

6. Technologies for remanufacturing

Main author: Politechnika Poznańska.

Challenges to CRM efficiency of household goods in Europe

The circular economy creates new opportunities for original equipment manufacturers (OEMs) to increase their supply chain viability, as end-of-use products can substitute supplies from far away, especially in the case of critical raw materials [30]. To enhance circularity, value-retention processes such as remanufacturing must be applied. Remanufacturing is an industrial process that restores used products to a condition that is indistinguishable from that of new. Currently, remanufacturing in PaaS is a niche practice in B2C markets. OEMs that create closed-loop systems must be able to perform disassembly, material reprocessing, reassembly, and remanufacturing in a cost-effective manner [31]. From the perspective of the retention and circulation of critical raw materials in remanufacturing, establishing a cascade model is crucial. The challenges arise from low product suitability for remanufacturing products, legislation, and policies focused on recycling. Furthermore, the existing take-back system for household appliances is driven by recycling, which results in products being damaged when collected and transported, making them unsuitable for efficient CRM recovery [32].

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 5.1 – Formulating research issues based on challenges in industrial cases, Task 5.2 – Developing a decision-making framework for efficient remanufacturing in PaaS, Task 5.3 – Developing a method for simulation modelling of leaner remanufacturing in PaaS settings, Task 5.4 - Testing the decision-making framework and the remanufacturing simulation, and Task 5.5: Generalizing learning outcomes on remanufacturing from industrial cases in WP5 –Remanufacturing research for PaaS.

The planned contribution included the development of a lean & green remanufacturing process for the use case and combining it with more efficient recycling to benefit from the cascade model and sustain CRM in the economy. The assessment of the challenges is intended to derive a support tool for companies to build capacity for CRM-efficient remanufacturing.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

PaaS changes the boundary conditions and creates a closed-loop system for remanufacturing with reduced uncertainty related to the availability of cores (supply side). PaaS is one of the most promising means for a resource-efficient circular economy and for increasing the efficiency of CRMs. In practice, there are relatively few examples of successful implementation of Product-as-a-Service models in the EEE sector on consumer markets B2C. With the application of a maturity model, we reviewed the PaaS offerings for household appliances in B2C in the EU regarding using the R strategies framework. Most offers about the R strategies are in a state of low or medium maturity, including obligatory end-of-life recycling, limited repairs, and some refurbishment operations [33]. The transition towards circular PaaS for EEE in consumer markets shall include a broader application of refurbishment and remanufacturing, such as VRP with high CRM resource efficiency and circularity. We applied a systematic literature review, gap analysis, and expert assessment to identify the key 12 challenges and 14 enablers (see Figure 7), which were translated into a decision support aid for OEMs to facilitate their transition to remanufacturing in PaaS [32].

The research involved disassembling and analysing a selected washing machine model (offered in PaaS) to determine which elements contain critical raw materials and in what quantities. For the washing machine use case, we performed manual disassembly and additional microscopic analysis to identify the components of washing machines with the highest potential for the CRM; see Figure 8.

The CRMs were identified in the internal computer, temperature sensor, and electrical system, including components such as diodes and contacts. In addition, critical materials were detected in the structural and mechanical parts of the washing machine, such as the pulley, drum bearing hub, drum bearing ball, drum shaft, drum cross member, and drum. The heating system, specifically the resistance wire of the heating element and its housing, was also found to contain these materials. Additionally, critical elements were observed in functional components, such as the door hinge, highlighting their widespread presence in different parts of the appliance. These results support the design of a reference simulation model for the remanufacturing process for household appliances. The simulation model (Figure 9) followed lean management principles to reduce the waste and non-value-adding activities in the process. The created simulation model is a hybrid one, as it includes the remanufacturing and recycling process for the use case. Furthermore, a reference model has been developed for the remanufacturing process of a generic household appliance. The model includes a set of key circular performance indicators (KCPIs) which allows it to manage the process in a more resource-efficient way.

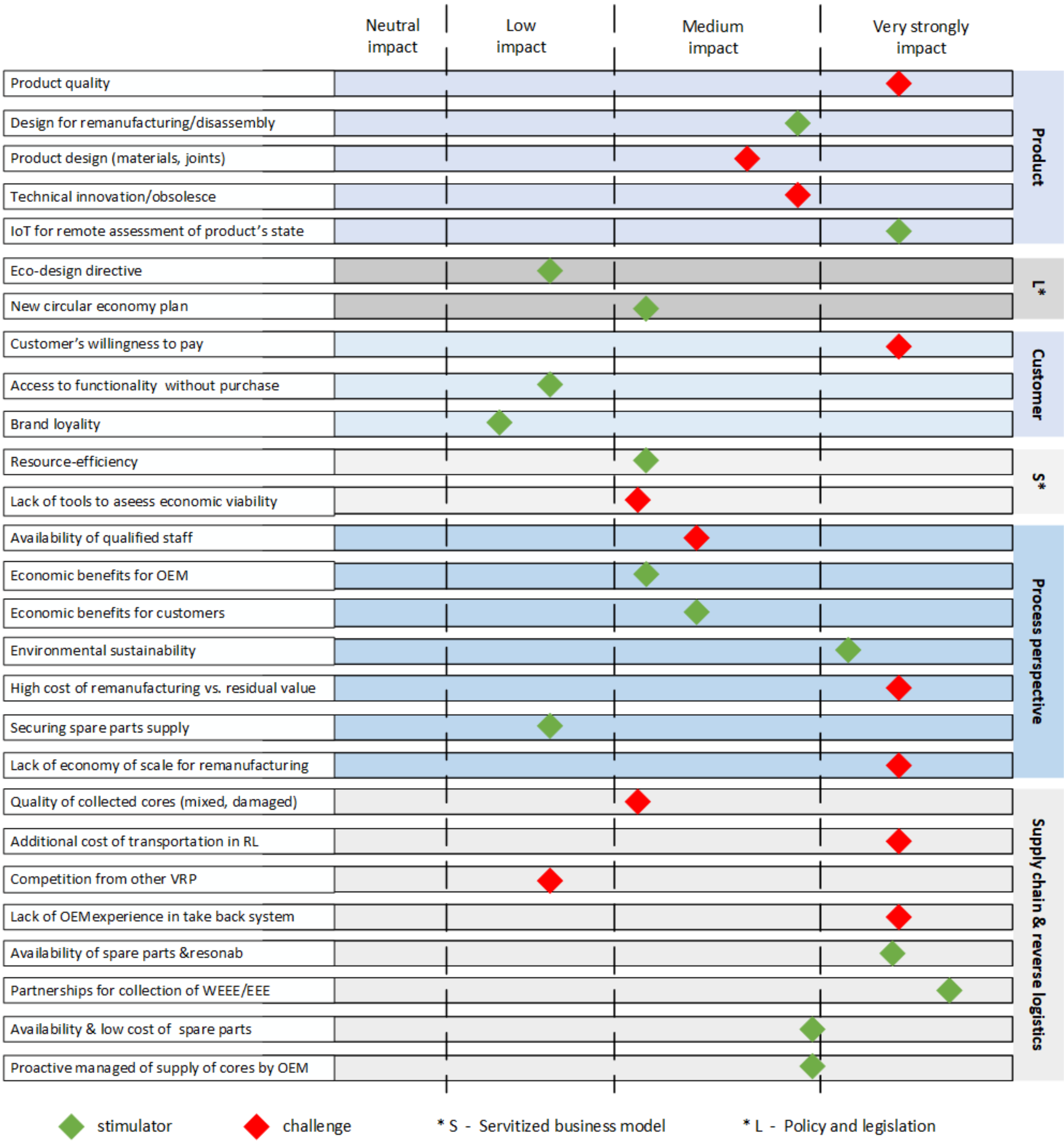


Figure 7. Significance of challenges (in red) and enablers (in green), according to experts [32]

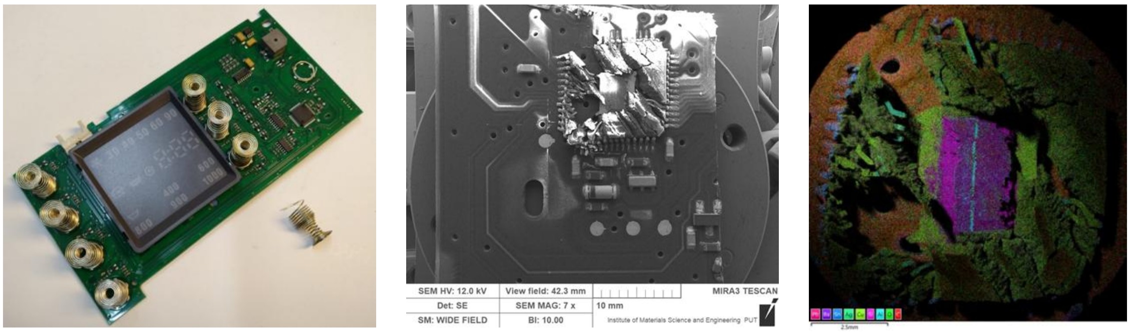
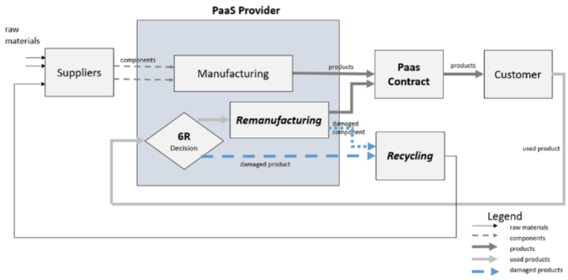
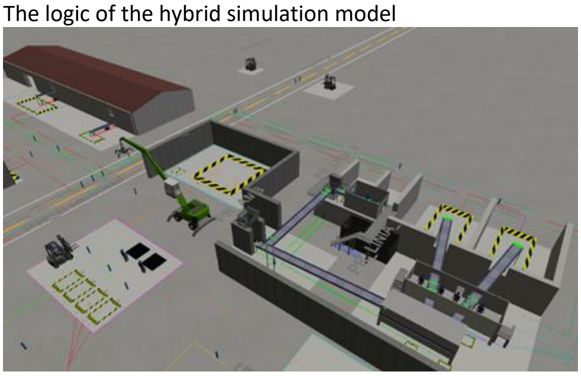


Figure 8. Example components from a washing machine, which includes CRMs (regular photo and SEM image)



The logic of the hybrid simulation model

Overview of the hybrid simulation model



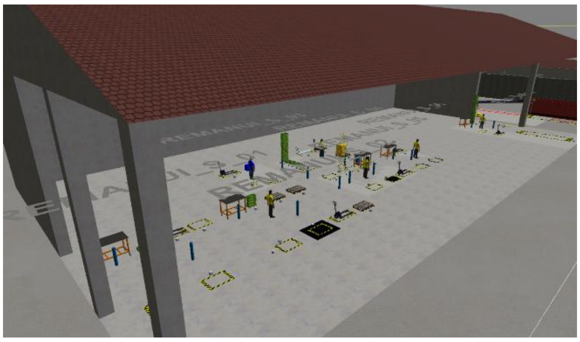


Figure 9. Presentations of the developed simulation model

The final step of the research was developing the capacity-building approach for practitioners named Rem-Cap-Up. We deploy the theoretical knowledge on remanufacturing in PaaS settings to existing recycling/reuse practitioners, aiming for workforce transformation towards a CE in the EU. In collaboration with an industrial partner, a set of assessment tools was developed within the Rem-Cap-Up model to support capacity building at both the individual level (employees at operational, tactical, and strategic levels) and the organisational level (resources, processes, and alignment with a PaaS strategy). The Rem-Cap-Up approach enables companies to identify existing capacity gaps and critical areas for the development of essential individual competencies, as well as the necessary organisational resources and processes required for effective remanufacturing within PaaS settings and the associated CRM efficiency.

Achievement/findings regarding the interdependent activities

Simulation research shows that a hybrid model for remanufacturing with recycling in PaaS allows for a resource-efficient state and more selective recovery of components with CRM content [34]. Control over cores in PaaS and cooperation in the organisation of take-back systems have the potential to establish the economy of scale for economically viable and environmentally beneficial remanufacturing in PaaS commonly carried out by OEMs on an industrial scale in B2C. The commitment of OEMs to progressively apply the principles of design for disassembly or design for remanufacturing will help overcome the limitations of linear products. OEMs can also benefit from the opportunity to create new sources of spare parts by scaling up the remanufacturing of EEE in PaaS. Remanufactured spare parts are commonly recognised in other industries (e.g., automotive) as a cost-efficient maintenance and servicing option. Moreover, they can help to recirculate CRM in the economy and reduce the demand for virgin CRM. In the current market conditions, the scenario with parts harvesting combined with efficient recycling is an interesting transition opportunity for OEMs to recover CRM. Full-scale remanufacturing requires the development of new skills for employees at the operational and managerial levels. In particular, the disassembly and quality assessment of returning products requires a technical knowledge that is lacking for the current employees. . The industrial and theoretical studies indicate that the practitioner's capability building in PaaS settings involves hybrid remanufacturing-recycling-repair scenarios. The current limited suitability of products for non-disassembly makes pure remanufacturing scenarios challenging. The transition to higher technology readiness levels (TRLs) shall be linked with the hybrid solution, especially in the transition period before the economy of scale can be reached for the PaaS model. Future research and innovation needed

Future research and innovation are needed to apply a PaaS model to other product categories and further generalise the knowledge obtained. Future research will include the application of multi-criteria decision-making techniques to provide the hierarchy of importance of indicators for remanufacturing with a focus on components with CRM in circular PaaS.

7. End-of-use product handling

Main author: Elektrorecykling S.A.

Challenges to CRM efficiency of household goods in Europe

In the sector handling waste electrical and electronic equipment (WEEE), we have observed significant design and material changes in many small and large household appliances. In the electrical equipment designed to eventually end up at a WEEE handling facility, we see a high level of component integration, which complicates material recovery. Based on our experience, new electrical and electronic devices entering the consumer market reach recycling firms as waste about 10 years later. Regarding design changes, we have noted that many components have been integrated over the past decade, significantly hindering or making remanufacturing or recycling unfeasible.

From our experience, we know that in recycling, component integration requires reprocessing the material through at least one or two additional lines to segregate post-recycling materials such as metals, non-metals, plastics, and printed circuit boards (PCBs) compared to a decade ago. These additional processes increase recycling costs. Design changes occur at the expense of changes in products. Table 1 shows the shift in washing machines over just a few years based on the data we have collected. It should be noted that washing machines from various manufacturers on the market were studied.

Table 1. Comparison of washing machines between 2019 and 2023 in their relative component weights (Source: Elektrorecykling S.A.)

Category	2019	2023
Steel scrap	33.7%	29.4%
Rubble	41.1%	42.2%
Polymer scrap	13.4%	14.7%
Engines	8.3%	7.3%
Cables	0.8%	0.9%
PCB	0.3%	0.5%
Waste	2.4%	5%

There is a common observation in the industry sector that modern household appliances often have shorter lifespans compared to older models. This is partly due to design changes that prioritize efficiency, cost reduction, and integration of components, which can make them less durable and more difficult to repair. Recent regulations such as Right to Repair aim to improve the durability and reparability of appliances, potentially reversing this trend. However, the current state often results in appliances being less resilient than their predecessors from a decade or more ago [35].

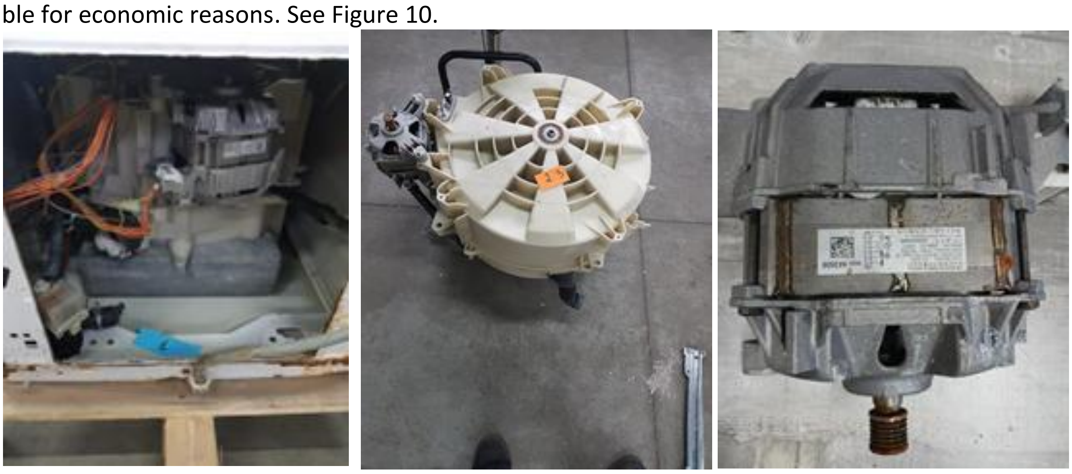
PaaS' contributions to CRM efficiency; planned for Scandere

It is assumed that PaaS will increase the efficiency of CRMs when used on a large scale. Manufacturers face the challenge of extending the lifespan of components and subassemblies, facilitating or even enabling the disassembly of components, and proposing innovative service solutions while maintaining a competitive and customer-friendly price. PaaS is assumed to positively impact reuse options, thereby enabling more efficient recycling, i.e., recovery of CRMs, allowing us to fully meet the requirements of a circular economy. The following planned task will be addressed in this section: Task 5.1 – Formulating research issues based on challenges in industrial cases in WP5 –Remanufacturing research for PaaS.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

In the project, we focused mainly on one Large Domestic Appliance (LDA), i.e., a washing machine, and a Small Domestic Appliance (SDA), i.e., a handy cordless vacuum cleaner. PaaS programs are currently being conducted on the market, e.g., at Papillon in Belgium, concerning access to energy-saving equipment (e.g., washing machines) that under-resourced families cannot afford. PaaS also concerns cordless vacuum cleaners on the German and Dutch markets, where customers can subscribe to the entire vacuum cleaner or just the battery for a monthly fee. In the case of both devices, the manufacturers will be responsible for a lot of the costs. A maintenance and service base would have to be created, which would significantly extend the life of EEE. From the manufacturers' perspective, this also involves a lot of construction effort.

Taking part in the dismantling of a washing machine, we see much scope for improvement. Many parts in the models currently available on the market have components integrated in such a way that in the event of a failure, instead of replacing a small component, the entire panel must be replaced, which is very uneconomical and the equipment, instead of being put back on the market, ends up in a landfill or ultimately for recycling. It is harder to get to valuable fractions of critical materials from integrated components. Sometimes, this causes a huge number of processes to be carried out, which in the end may not be profitable, so reaching the CRM will not be possible for economic reasons. See Figure 10.



Drum with engine | Drum with engine | Engine

Figure 10. Dismantled washing machine

On the other hand, with smaller EEE, the so-called SDA, and lower purchase costs, the PaaS model may be more economically complicated and less profitable. Additionally, with battery-powered equipment, there is a problem with the transport of batteries that are no longer working, which is problematic due to the possibility of spontaneous combustion [36, 37].

However, the PaaS model will provide a controlled return of batteries, which will be easier to collect and recycle for recovery, e.g., cadmium, lithium, and nickel. On the other hand, the equipment that will reach us to processing plants will be segregated and, therefore, should represent a greater economic value. A recent investigation has shown that there is currently a shortage of qualified places providing reuse and repair services [38]. However, the establishment of service and maintenance places will absorb significant financial outlays both in creating such places and training appropriately qualified personnel. Who should then be responsible for creating such places: producers, recyclers, or the state?

Any difference between the plan and the achievement/findings? Why?

There are always a lot of inconsistencies between assumptions and reality. First, the PaaS model generates many more operational activities and challenges than initially assumed. It causes a number of additional financial outlays for the manufacturer compared to one-off sale. In the PaaS model, more emphasis should be placed on the service life of components in SDA and LDA devices than is currently the case. Without this, PaaS models may be financially unsatisfactory and simply impossible.

Achievement/findings regarding the interdependent activities

The project includes many interdependent activities. Starting with greater durability of components, which will ensure lower maintenance and service costs, and then robotization options in diagnosing and servicing devices. Robotization can significantly increase the profitability of PaaS models and reduce the need for specialist staff. It follows that improving the efficiency of CRMs results from a holistic view that includes ecodesign with an emphasis on more durable components, automation, and effective qualified recycling.

Future research and innovation needed

For PaaS to function, it is necessary to create qualified places providing reuse and repair services, of which there are not many across the EU. There is a shortage of automatic equipment for dismantling SDA and LDA. On the consumer market, there is a lack of qualified companies providing services for collecting, sorting, and recovering critical materials in Europe [39]. Also, current recycling rates for CRMs are low, with an average end-of-life recycling input rate of 8.3% across the identified materials (ibid). These places exist, but there are too few of them.

In our opinion, there is a lack of reverse logistics for individual consumers. As a company from the recycling industry in constant contact with environmental services, we can admit that environmental protection legislation does not keep up with market developments and inhibits them.

The need for research and innovation is presently at its peak. The implementation of the PaaS model on a larger scale may completely change the electronics market. It will result in a different approach to the design of devices and the entire system of collecting and segregating WEEE and recovering CRM, which will be crucial in the production of further EEE and batteries. Therefore, the scope for research and innovation in the above areas is very wide.

8. Technologies for recycling

Main author: Katholieke Universiteit Leuven.

Challenges to CRM efficiency of household goods in Europe

As the demand for electronic devices continues to rise, so does the urgency to address the challenges of resource scarcity and waste management. Critical raw materials (CRMs), essential for modern technologies, are at the heart of this challenge. In Europe, inefficiencies in collection, recycling, and recovery processes, along with short product lifespans, limit CRM efficiency [40]. To meet the goals set by the European Commission's Critical Raw Materials Act (CRMA) [41] and the Circular Economy Action Plan (CEAP) [42], innovative approaches are needed to ensure the efficient recovery and reuse of these critical resources, as well as policies that promote durable product design and circular business models.

PaaS' contributions to CRM efficiency; planned for Scandere

The following planned tasks will be addressed in this section: Task 6.1 – Formulating research issues based on challenges in industrial use cases from WP1, Task 6.2 – Developing methods to evaluate product designs for ease of robotic dismantling, and Task 6.3 – Developing novel product designs with fasteners and robotic treatment processes, and Task 6.4 - Evaluating robotic treatment processes and novel product design prototypes for use cases in WP1 in WP6 – Recycling research for PaaS.

The plan is to leverage the latest scientific advancements to enhance PaaS' contribution to CRM efficiency, focusing on improving products and services through innovative solutions. Insights from key research in remanufacturing and industrial product/service systems will be applied to assess the applicability of these solutions across different PaaS offerings, including vacuum cleaners. As part of this effort, novel methods will be developed to evaluate the ease of robotic disassembly and dismantling, incorporating criteria specifically relevant to robotic operations. To validate these methods, the robustness and time efficiency of robotic disassembly, dismantling, and manipulation will be tested on both original products and prototypes integrating newly developed fasteners.

PaaS' contributions to CRM efficiency; achieved/found in Scandere

A key factor in establishing an economically viable PaaS model is designing products for both manual and robotic disassembly. To support this, methods were developed to assess product designs for the human-robot cooperative disassembly system (Figure 12). The work expands the existing Ease of Disassembly Metric (e-DiM) [43], providing designers, policymakers, and recyclers with a tool to anticipate the industrialization of such systems. To develop this metric, a set of criteria was established to determine which operations can be effectively performed in a flexible system. This led to the creation of the Robotic Ease of Disassembly Metric (Re-DiM) [44], which evaluates both manual and robotic disassembly times comprehensively. To validate Re-DiM, the ease of disassembly was assessed for key components of a Bosch Roxxter robotic vacuum cleaner (Figure 11). Experts identified two target components: the battery and the motor. The battery, with a shorter lifespan and 1-year warranty, is a primary candidate for replacement, while the motor, with a longer 10-year warranty, is considered for potential reuse. Both components also contain critical raw materials (Nd, Ni, Cu, Li, and Co). The findings highlight current robotic disassembly challenges and emphasize the importance of innovative design approaches to enhance robotic disassembly efficiency.

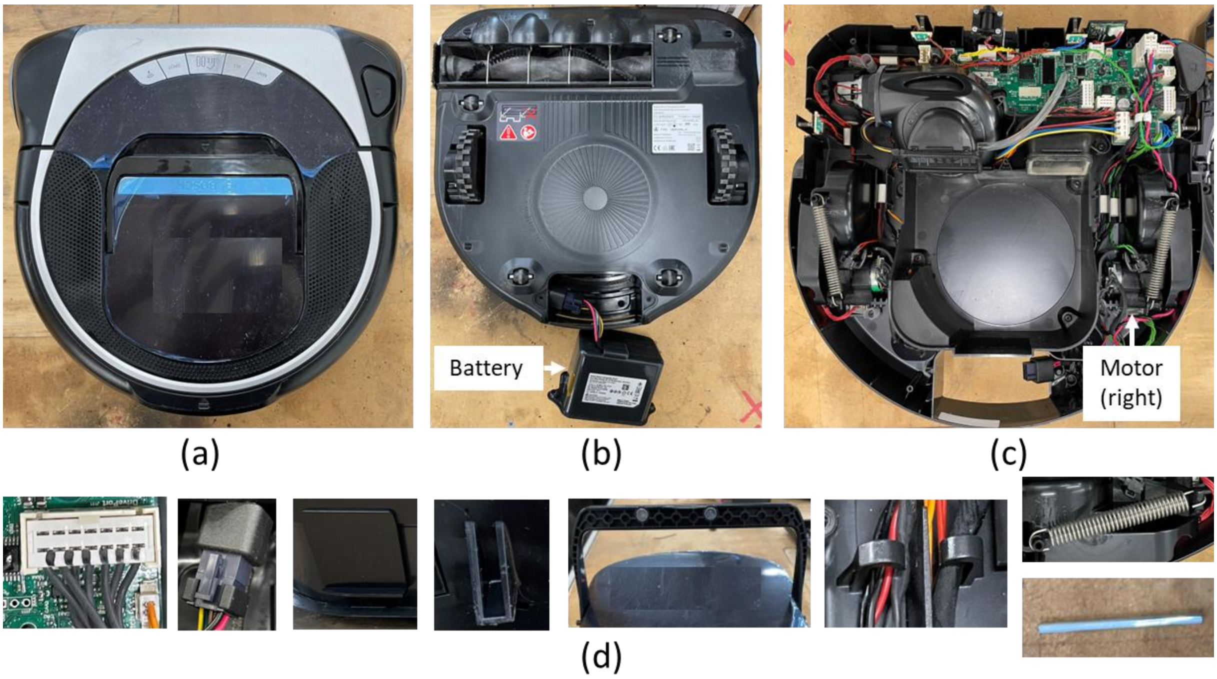


Figure 11. (a) Bosch Roxxter robotic vacuum cleaner, with the following critical components: (b) Battery, (c) Motor, and (d) Connectors (clockwise from top left - PCB connector, cable plug, Snap-Fit 1 & 2, hinge, cable hook, spring & metal pin)

To create novel product designs with improved fastening and robotic treatment processes, an iterative approach was followed, incorporating ecodesign principles and the Re-DiM metric. The redesign process was guided by a set of generalizable design guidelines aimed at improving robotic disassembly efficiency. Below, some examples are presented:

- Ensure that parallel grippers can release connectors: Certain cable plugs were initially not compatible with robotic grippers due to their small gripping surface and release mechanism. To address this limitation, redesigned connectors included sufficient surface area for secure grasping by parallel grippers. Additionally, an alternative design modified the release mechanism so that disconnection could be achieved by robotic manipulation (by applying inward force instead of outward force).
- Facilitate multidirectional access to critical components: Battery fasteners were originally positioned on the bottom of the product, requiring product rotation for removal. The redesigned configuration allows battery removal from both the top and bottom, aligning with other critical components and streamlining the disassembly process.

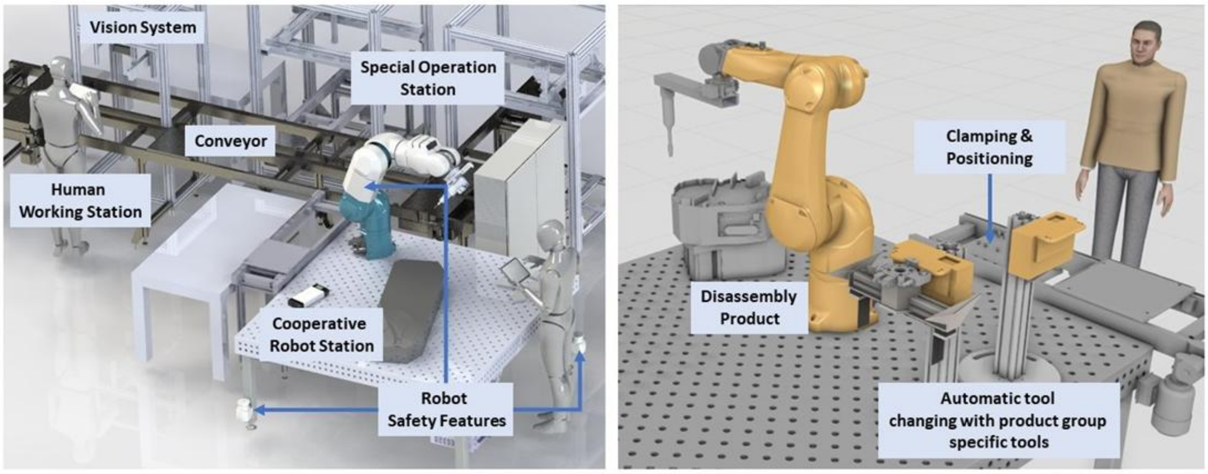
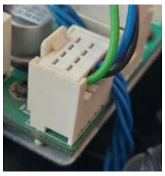
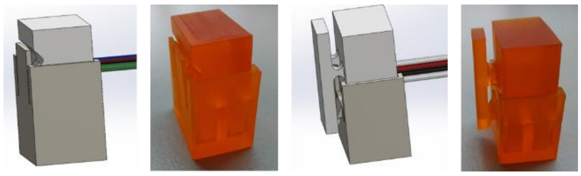
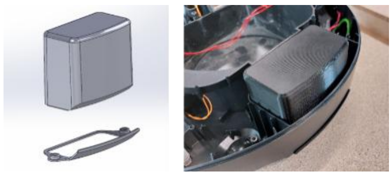


Figure 12. Demanufacturing cell for Flexible Remanufacturing Systems (Re-FMS)

- Avoid disassembly steps requiring simultaneous two-hand operations: Certain cable connections required one hand to hold a component (e.g., the top cover) while the other disengaged the connector, making robotic removal impractical. To overcome this, spring-loaded connectors were implemented, allowing automatic disconnection when the component is lifted by the robot.
- Enable automated cable removal from retention features: the original cable hooks did not allow robotic extraction due to limited clearance for the gripper manipulation. To improve this, two alternative designs were considered. A clamp mechanism that opens when cables are either pushed in or pulled out, allowing robotic handling without requiring additional tools. A U-shaped clamp that can be released when it is squeezed from the sides and lifted, making robotic removal feasible.

Prototypes incorporating these redesigns were developed and tested to assess their impact on robotic dismantling efficiency (see Table 2). As part of Task 6.4, these solutions were evaluated in practical use cases (i.e., the robotic vacuum cleaner), demonstrating improvements in robotic disassembly times and CRM recovery rates. The findings highlight the benefits of applying structured design guidelines to enhance robotic disassembly feasibility, supporting PaaS and circular economy strategies.

Table 2. Comparison between original design and redesign/prototype

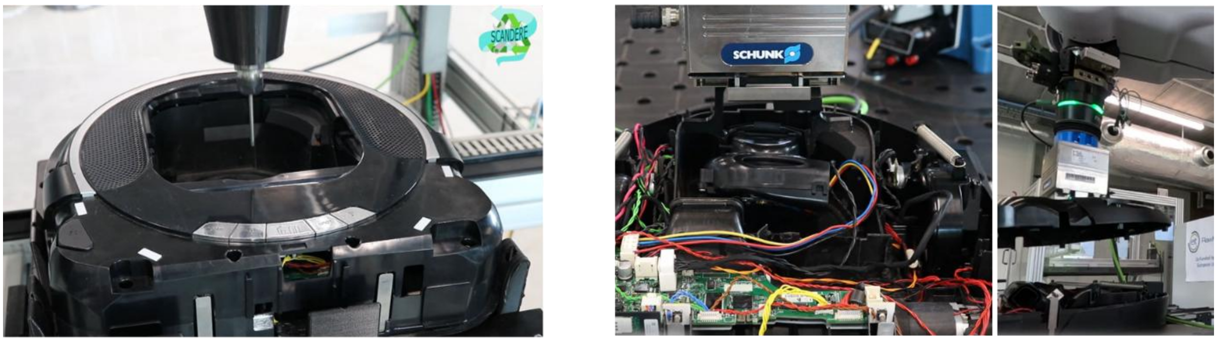
Original design	Redesign/prototype
Electrical connectors 	
Battery assembly 	

Top cover 	
Cable hooks 	

Any difference between the plan and the achievement/findings? Why?

Based on the results from WP3 Deliverable 3.1, the one result was that Lithium (Li), Cobalt (Co), and Nickel (Ni), all CRMs from the vacuum cleaner battery, have the highest environmental impact, and are currently not collected in an efficient means. “Consequently, it becomes evident that there is a pressing need to enhance collection and recycling processes for lithium and rare earth metals.” (Scandere WP3 Deliverable 3.2). The battery cell extraction concept was modelled to address this key challenge.

The findings went further than assessing the ease of robotic disassembly by implementing and testing redesign solutions (see Figure 13). This iterative process not only measured improvements in manual and automated disassembly but also showed that a robotic arm could efficiently recover CRM-rich components. The redesign kept the product’s functionality while providing the feasibility of scalable human-robot cooperative disassembly for circular economy applications.



(a) (b)

Figure 13. (a) Robotic unscrewing (b) Robotic component removal

Achievement/findings regarding the inter-dependent activities

The challenges in CRM efficiency are strongly influenced by interdependent activities. In our study, ecodesign principles were applied alongside the Re-DiM metric to iteratively assess and enhance the ease of human-robot cooperative disassembly in vacuum cleaner redesigns. The findings highlight that improved disassembly efficiency directly impacts multiple sustainability goals.

One important interdependency that was not fully exploited in this work is the use of product data within the PaaS framework. PaaS providers retain ownership of the products, which gives them access to detailed design data such as the location of connectors, materials information, and maintenance records. This data could be used to optimize robotic disassembly strategies by enabling adaptive planning, customized robotic toolpaths, and predictive maintenance. Although this work focused on physical redesign improvements, incorporating product data would further enhance CRM recovery efficiency.

These findings have led to the development of design guidelines aimed at improving CRM efficiency. The results demonstrate that achieving higher CRM efficiency is not the outcome of isolated efforts but rather the result of a holistic approach where design, automation, and resource recovery are closely interconnected.

Future research and innovation needed

PaaS has the potential to transform traditional ownership models that would allow a better collection of broken products that could then be refurbished, repaired, or recycled by the manufacturer to extract the highest percentage of CRMs, while also providing the customer with an attractive option. Currently, the cost of these B2C PaaS offerings is unattractive for most consumers; however, the higher extraction rate of CRMs through such offerings could help reduce these costs.

Future research will explore innovative design approaches to redesign products across diverse product families. Additionally, more detailed comparative assessments of disassembly times will be conducted to identify best practices, further validate the applicability of the proposed Re-DiM metric, and refine them when necessary. Efforts will also focus on refining the reference times for robotic disassembly through further empirical experiments using the Re-FMS demanufacturing cell currently under development. The ultimate objective is to establish comprehensive design guidelines that facilitate not only efficient manufacturing but also streamlined repair, reuse, remanufacturing, and recycle. Simultaneously, the research will explore opportunities for enhancing the ease of disassembly information in Digital Product Passports and approaches for the deployment of DPPs that contain Re-DiM information at diverse stages of the product lifecycle. To further strengthen the link between design and end-of-use processing, future research should also explore how digital product data from PaaS can be used to improve disassembly planning and automation.

9. Deliverables

All the planned deliverables are listed below with their status as COM (completed), REV (under internal review), or WIP (work in progress).

No.	Lead partner	Deliverable title and description (in case of publication, title and other information is added)	Type	Diss. level	Status
D0.1	LiU	Consortium Agreement completed	REP	CO	COM
D0.2	LiU	Plan for communication, dissemination, and exploitation (PCDE)	REP	CO	COM
D0.3	LiU	Project website and LinkedIn and ResearchGate pages launched	DEC	PU	COM
D0.4	LiU	Annual project progress report, incl. updated PCDE – Year 1	REP	PU	COM
D0.5	LiU	Annual project progress report, incl. updated PCDE – Year 2	REP	PU	COM
D0.6	LiU	Popular scientific communication on findings from assessment on CRMs	DEC	PU	COM
D0.7	KUL	Popular scientific communication on CRM efficiency in recycling	DEC	PU	COM
D0.8	LiU	A package of multi-media marketing and pedagogical briefings	DEC	PU	COM
D0.9	LiU	Final project report, incl. PCDE – Year 3	REP	PU	COM
D1.1	BSH	CRM efficient PaaS demonstrator 1 – Washing machine	DEM	PU	COM
D1.2	BSH	CRM efficient PaaS demonstrator 2 – Vacuum cleaner	DEM	PU	COM
D1.3	LiU	CRM efficient PaaS demonstrator 3 – Robotic lawn mower	DEM	PU	COM
D1.4	LiU	Report on CRM efficient PaaS business models (for journal paper) • Enhancing Critical Raw Material Usage through Battery Cell Extraction and Reuse. Submitted to PLATE2025, will be open access via AAU Open publishing by August 2025.	REP	PU	COM
D2.1	CaR	Recommendations for PaaS regulations on CRMs	REP	PU	COM
D3.1	LiU	Results from LCC of a CRM efficient PaaS case (for conference presentation) • Product as a Service of household appliances – Making the use of critical raw materials more efficient, The 32nd CIRP Conference on Life Cycle Engineering, 2025. • Supporting the Transformation to Access-Based Business Models in a Circular Economy with a Practical Model for Calculating the Costs of the Provider, The 11th Swedish Production Symposium, 2024.	DEC	PU	COM
D3.2	LiU	Report on sustainability assessment of one case (for journal paper) • Lifecycle design of integrated product-service systems by addressing different technical lifetimes of product components for resource efficiency, to be submitted to a journal.	REP	PU	COM

		• How can manufacturers identify the conditions for financially viable product-as-a-service? Frontiers in Manufacturing Technologies, 2024.			
D3.3	LiU	Report on assessment of CRM efficient PaaS models (for journal paper) • Social sustainability of a home appliance product-as-a-service for a circular economy, Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, System Analysis and Logistics 2025, journal, forthcoming.	REP	PU	COM
D4.1	IPG	Report on identified design research issues (for conference presentation) • An exploratory study for product-as-a-service (PaaS) offers development for electrical and electronic equipment. Procedia CIRP, 122, 521-526, 2024. • Measuring the level of acceptance from the population of Guayas Province for different PaaS models: The case of the washing machine. Procedia CIRP, 116, 462-467, 2023. • Leveraging circularity through repair standards: A comparison of methods for assessing product reparability for extended use on mechanical products. Procedia CIRP, 120, 273-278, 2023. • Product-as-a-service for critical raw materials: challenges, enablers, and needed research. Going Green: CARE INNOVATION, 2023.	DEC	PU	COM
D4.2	IPG	Concept for the design platform (for conference presentation) • Design platform concept for product-as-a-service by electrical and electronic equipment manufacturers. Procedia CIRP, 130, 1176-1181, 2024.	DEC	PU	COM
D4.3	IPG	Concept for the design method (for conference presentation) • Facilitating circularity: challenges and design guidelines of Product-as-a-Service (PaaS) business model offers for electrical and electronic equipment. Procedia CIRP, 128, 567-572, 2024. • Towards user-centric design guidelines for PaaS systems: the case of home appliances. In European Conference on Software Process Improvement (pp. 186-195). Cham: Springer Nature Switzerland, 2023	DEC	PU	COM
D4.4	IPG	Application of the design platform to cases (for journal paper) • Component-as-a-Service for Electrical and Electronic Equipment: Business Model, Circularity, and Design Implications. In European Conference on Software Process Improvement (pp. 62-75). Cham: Springer Nature Switzerland, 2024. • Parametric LCA integrating a product's State of Health: A decision-making tool based on environmental impact in the context of circular strategy. Procedia CIRP, 122, 199-204, 2024.	REP	PU	COM
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D5.1	PUT	Report on identified remanufacturing research issues (for conference presentation) • Challenges and research issues for remanufacturing in PaaS – from literature review to the industry perspective" – 27th International Conference on Production Research, Cluj-Napoca, Romania • Stimulators of transition toward circular supply chain Exploratory studies in Electrical and Electronic Equipment industry. LogForum, 20(1), 83-96, 2024. Assessment of the maturity of product-as-a-service business models for household appliances from the perspective of R strategies in Circular Economy. Procedia CIRP, 122, 1083-1088, 2024.	DEC	PU	COM
D5.2	PUT	Decision-making framework including guidelines to enhance remanufacturing (for journal paper) • How can OEMs scale up remanufacturing in product-as-a-service (PaaS)?– challenges and enablers from a theoretical and industrial perspective. International Journal of Production Research, 1-30, 2024. • Enablers and barriers in building the circular supply chain through remanufacturing - Grey DEMATEL approach, International Journal of Production Economics, 2025. • Assessment of the potential for remanufacturing of a washing machine with focus on critical raw materials, submitted to 15th IFAC Workshop on Intelligent Manufacturing Systems to Koszalin, Poland, 2025. • Remanufacturing of household appliances in PaaS – a decision framework with indicators to support the circularity, accepted ford to 15th IFAC Workshop on Intelligent Manufacturing Systems to Koszalin, Poland, September 11-12, 2025.	REP	PU	COM
D5.3	PUT	Concept for the simulation method (for conference presentation) • A new method for simulation modelling of leaner remanufacturing in PaaS settings. Procedia CIRP, 122, 939-945, 2024.	DEC	PU	COM

		Scientific and Practical Challenges for the Development of a New Approach to the Simulation of Remanufacturing. Sustainability, 16(9), 2024.			
D5.4	PUT	Simulation method for remanufacturing incl. recycling (for journal paper) Simulation method for remanufacturing including recycling – testing and project dimensioning, submitted to Management and Production Engineering Review – under review.	REP	PU	COM
D5.5	PUT	Report on practitioners' capacity building (for journal paper) • Model for practitioners' capacity building for remanufacturing in product-as-a-service (PaaS), P. Golinska-Dawson, K. Werner-Lewandowska - draft version of paper accepted and presented at the 7th International Conference on Remanufacturing (ICoR), 8-10 April 2025, in Amsterdam (with e-proceedings), the revised version submission to Journal of Remanufacturing	REP	PU	COM
D5.6	PUT	Educational manual for practitioners' capacity building	DEC	PU	COM
D6.1	KUL	Report on identified recycling research issues (for conference presentation) • Product-as-a-service for critical raw materials: challenges, enablers, and needed research. Going Green: CARE INNOVATION, 2023.	DEC	PU	COM
D6.2	KUL	Concept for methods, product designs, and processes for recycling (for conference presentation) • Robotic ease of Disassembly Metric (Re-DiM) for human robot cooperative disassembly: A case study for a vacuum cleaner, Procedia CIRP, Volume 122, Pages 677-682, 2024. • Robotic Ease of Disassembly Metric (Re-DiM) for Flexible Cooperative Remanufacturing of Bike Batteries. In: Secchi, C., Marconi, L. (eds) European Robotics Forum 2024. Springer Proceedings in Advanced Robotics, vol 33. Springer, 2024.	DEC	PU	COM
D6.3	KUL	Methods to evaluate product designs for recycling (for journal paper) • Ease of Robotic Disassembly Metric (Re-DiM) and information for digital product passports in Flexible Remanufacturing Systems (Re-FMSs), Journal of Sustainable Production and Consumption, in review.	REP	PU	COM
D6.4	KUL	Laboratory evaluations of novel fastener design prototypes (for journal paper) • For conference presentation - Ecodesign for Critical Raw Material recovery: enabling robotic disassembly of small appliances. The Going Green EcoDesign2025 e-book proceedings, abstract submitted	REP	PU	COM

Conclusions and outlook

This technical report highlighted results from the Scandere project. Each section showed the challenges, achievements, and future work in the corresponding area. It also described inter-relations between different areas of relevance. The vision of the Scandere project has been "**PaaS designed by Europe, increasing resource and cost efficiency and retaining CRMs in Europe!**" With this vision in mind, the expected impacts of the project require further investment, where the key exploitable results (KERs) are identified from the project plan and pathways are exemplified in Table 3.

Table 3. Expected impacts of the project and their pathway examples

Impact	KER	Pathway example	Measurement
Increasing CRM efficiency & security	1,3 (4,5)	Companies outside Scandere **implementing economically and environmentally conscious PaaS**. More **closed loops for CRM flows**.	LCA per functional unit of products. Reuse & recycle rates.
Improving social sustainability	1, 3	Companies outside Scandere **implementing socially-conscious PaaS.**	Social LCA.
Decoupling economic growth from using CRMs	1,3 (4,5)	Companies outside Scandere **implementing economically and environmentally conscious PaaS**.	Production of economic value over CRMs used.
Improving nontechnological framework conditions	2	**Influencing EU policy makers** on circular business models with research-based evidence.	# & quality of interventions to EU regulations.

Note: (4,5) means that KERs 4 & 5 are around TRL4 (as planned), while other KERs are around TRL6 or higher.

Part of the described future work is here repeated.

- Deploy the double-system perspective for CE research and innovation.
- Integrate LCA, LCC, and S-LCA for guiding design choices.
- Apply multi-criteria decision-making to better handle complex situations.
- Apply a PaaS model to more product categories and further generalise the knowledge.
- Hold dialogues with EU policy makers (e.g., via policy briefs) on CE business models.
- Create and develop qualified workforce and organizations for reuse, repair, and remanufacturing.
- Consider economic infrastructures (incl. private and public parties) in policy making.
- Increase the TRL for automation of dismantling products.
- Align with other tools, e.g., Digital Product Passports, in CE research and innovation.

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Contact and information

Tomohiko Sakao tomohiko.sakao@liu.se (PI)

Theresa Apelqvist theresa.apelqvist@liu.se (Communicator)

More information is available at Raw Materials Information System (RMIS), scandere.nu , and the LinkedIn page (via the QR code below).

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