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Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases

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Abstract. As the need for more responsible production and consumption grows quickly, so does the interest in the concepts of eco-efficiency and circularity. To make swift progress towards sustainability, solutions must be developed and deployed at scale. It is therefore critical to understand the challenges faced by industry to accelerate the uptake of best practices for circular and efficient production systems. This paper presents the emerging issues from three industrial pilots in an on-going collaborative project. We discuss and suggest further work around crucial questions such as: How to deploy circular solutions from lab to industrial scale? How can digitalization support efficient circular processes?

Keywords: Sustainable Development; Circular Economy; Resource efficiency; Recycling; Remanufacturing; Reuse.

1 Introduction

1.1 Background

Circular economy (CE) is an umbrella concept [1] promoting the retention of economic and environmental value of materials. The aim is to keep products in productive use for longer or to recapture materials in loops to give them a new life as products. Ideally, waste should systematically be seen as a resource and source of value [2]. Consequently, the benefits of CE align with the UN Sustainable Development Goals focusing on environmental impact reduction [3]. Several circular strategies were proposed to define the practices associated with different loops and targeting different parts of the value chain [4,5]. CE is well-defined [4,6] and typically focuses on products' end-of-

life; e.g. reuse, repair and remanufacturing to retain the value embedded in materials for as long as possible. They further include industrial waste management strategies, such as industrial symbiosis [7], and regenerative approaches, such as biomimicry [8,9]. These strategies offer opportunities to decouple the environmental impact from the value delivered to customers and captured by businesses.

1.2 Knowledge Gap, Project Aim and Research Question

As the literature and examples of CE grow, the feasibility and benefits are becoming clearer. But our society is still largely linear and circular solutions are still the exceptions rather than the industrial norm. While inspiring CE ideas exist, they are often theoretical, experimental, isolated cases, or difficult to replicate [10,11]. Transitioning towards CE requires a paradigm shift [12,13], complex structures often relying on collaboration between organizational functions and between stakeholders along the value chain. This complexity presents additional challenges to create procedures to formalize and coordinate collaborative efforts. Many researchers have recognized different types of barriers, such as technological, financial, organizational, operational, etc. [14–16].

To support companies in their sustainability efforts, the project presented in this paper aims to identify and overcome the challenges they face in adopting circular and eco-efficient solutions. Accordingly, the overarching research question for this project was: How can technology development support efficient circular solutions and enable their uptake from lab to industrial scale?

1.3 Project Structure and Study Designs

This paper presents empirical findings from three case studies exploring novel circular solutions as part of a collaborative project between industry and academia: Enabling REuse, REmanufacturing and REcycling Within INDustrial systems (REWIND). The project structure is described in **Fig. 1**. Each case study employed different study designs and empirical methods to address the specific needs and conditions of each case. Pilot 1 was exploratory, qualitative business research. Pilot 2 was applied research focusing on technology development in a robot lab. Pilot 3 was an early-stage techno-economic analysis based on experimental research in a chemistry lab.

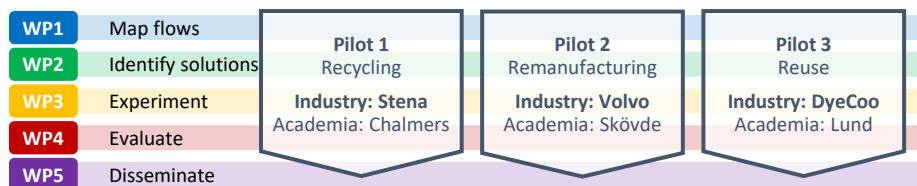


Fig. 1. Project structure and study design.

The next section presents the findings from the pilots (WP1-2) and the barriers encountered in developing circular solutions (WP3-4). We then discuss these barriers and suggest further work to realize, scale-up and systematize these solutions (WP5).

2 Emerging Issues from Industrial Pilots

2.1 Business Case for High-Value Recycling of Cooling Appliances

The first industrial pilot focused on recycling Waste from Electrical and Electronic Equipment (WEEE). Today, Stena Recycling handles a wide range of WEEE products. If managed improperly, WEEE can negatively affect the environment and human health [17]. In Sweden, it is the responsibility of end users to transport end-of-life refrigerators to collection centers. The WEEE collected from Sweden, Denmark and Norway is then transported to Stena Nordic Recycling Center. The current collection system does not promote value-retention, as the refrigerators are stored outdoors, where valuable components can be damaged or stolen, depleting the products of their potential value. Retaining the value of end-of-life refrigerators requires better integration across the supply chain, along further development and improvement of the collection centers.

At the Stena Nordic Recycling Center, the preparation processes for treating refrigerators are cleaning (removal of fridge contents), separation (removal of cables) and evaluation (registering of missing pieces such as doors and/or compressors). Today, the refrigerators are manually marked to identify the required recovery processes. Then cooling agents and oil are extracted from the system. The compressor is removed, drilled and drained in a mostly manual process. Finally, the refrigerator skeleton is fed to a shredding machine and materials sent for recycling. Advanced technologies could support operators directly in the more complex or dangerous processes. Stena is currently exploring the potential of physical and cognitive automation (e.g. robotics, machine vision and learning) to aid recovery processes. For example, compressors are valuable components but collecting them is labor intensive (high levels of know-how and physical efforts). Physical automation could prevent injuries and accidents while increasing the efficiency of and value recovered from the dismantling process.

All the refrigerators arriving at Stena's facilities are considered as end-of-life products. However, the intention to transition towards a more CE has led to interesting discussions suggesting that refrigerators could be remanufactured and refurbished as alternatives to recycling for value recovery. Implementing these alternatives requires operators' upskilling. Thus, alternative sources of value for social sustainability exist at organizational level through the use of digital training tools, such as AR/VR [18].

Finally, capturing data from end-of-life products as a source of value (e.g., brand, model, and product lifetime) could be appealing to manufacturers. This possibility was explored in similar studies attempting to achieve traceability for producers as a potential business model for post-consumer recycling [19]. However, commercializing data from products and enabling collaboration along the value chain also present a number of challenges for Stena. For instance, the placement of the compressor and information labels are not standardized between different brands and models of refrigerators, thereby hindering data capture and process automation. As of today, the process of identifying the product and its components requires extensive manual intervention. The data required to teach AI to recognize the product and assist in automating the compressor removal would require a database of at least 100,000 images. Gathering this data is demanding and the benefits still unclear.

Stena continuously strives to innovate and achieve more sustainable recycling processes. However, efforts are currently limited to an organizational level. Collaboration with manufacturers, collection centres and other logistics actors is still difficult in the absence of incentives to promote it (e.g. regulations, standards or market forces). CE is gaining attention, but the supporting information flows for collaboration are not yet in place. For example, leading manufacturers, such as Electrolux, focus on new product designs using recycled materials; but efforts to tackle problems at the products' end-of-life are comparatively low, especially considering that the majority of refrigerators reaching recyclers today were designed and manufactured a decade ago or more. This delay between design improvements for end-of-life management and their benefits present a major barrier for collaboration between manufacturers, collection centres, recyclers and other actors in circular value chains to tackle today's WEEE at scale.

2.2 Operator Support for Remanufacturing Truck Components

The second industrial pilot targeted remanufacturing operations at Volvo focusing on "giving a new lifecycle" to components from their previously manufactured truck engines. Remanufacturing begins with an order from customers. The product previously collected is taken into the remanufacturing line consisting of five major processes: disassembly, cleaning, machining, reassembly, and quality control. In the disassembly process, all components are removed and classified. Some components are systematically discarded (e.g. wiring harnesses, air harnesses, sensors, camshafts). The main parts are cleaned and assessed whether they can be reused or must be replaced. Parts that must be reprocessed to meet quality standards are sent to machining stations. The components are then reassembled using reprocessed parts and new parts. Finally, the product goes to a quality control station before being delivered to the customer.

Remanufacturing is a highly variable and complex operation at the task level. Most of the remanufacturing-related knowledge is tacit. However, analysis and evaluation are usually more effective and meaningful when knowledge is explicit [20]. This pilot aims to convert this tacit knowledge into digitalized, explicit knowledge. Once transformed, this knowledge can be standardized in content and form, and presented to the worker using head-mounted augmented reality (AR) devices.

The central piece of this solution is an industrial internet of things (IIoT) platform used as a scalable medium. It retrieves up-to-date information for the operation at hand from the product lifecycle management platform and sends it to the AR device. This information (dis/assembly instructions) is displayed in AR as overlaid 3D objects, animations, text, audio or a combination of them. The IIoT creates dependencies between connected industrial equipment or retrieve worker's feedback for future improvements. Moreover, the IIoT platform can be used to perform data analytics enabling data-driven CE-related improvements. Ideally, this AR solution will offer benefits related to increased efficiency and effectiveness [21] as well as new opportunities enabled by data continuity and cloud-based systems [22,23] including improvements on scalability, adaptability, and cybersecurity. Furthermore, data continuity can provide a systematic approach to standardize critical operations that have high environmental impacts when performed sub-optimally.

An *ex-ante* evaluation identified technical challenges hindering successful implementation, including the implications of a foundational change in tools used in the process; for instance, considerable investment, implementation ramp-up, or human implications. Furthermore, several technology-related challenges have become apparent in this pilot. For instance, the complexity introduced from a data and information perspective requires upskilling of the IT department. In addition, few companies have developed feasible AR and IIoT products and their maturity in industrial environments is still limited. Complementary technologies, such as object tracking or environment understanding in AR, need to be improved to further exploit the potential of this solution.

2.3 Efficiency and Reuse in Textile Dyeing Processes

The third pilot explored a novel process to dye natural fibers. Textile production is a major contributor to water pollution as water is the most common dyeing medium. Although end-of-pipe technologies progressed well to prevent effluents and chemicals from entering the environment (e.g. zero liquid discharge and zero discharge of hazardous chemicals), equipment price and running costs can be expensive. Besides, zero-liquid discharge processes are energy-intensive and increase energy-related emissions. Moreover, solid wastes are still produced and difficult to treat.

A new dyeing process was introduced in the 1980s using a supercritical fluid as a dyeing medium [24]. It provides easy separation from chemicals, further allowing recirculation and reuse of the supercritical fluid and dyes at a low energy cost. Carbon dioxide is frequently used as supercritical fluid for dyeing because of its low critical point (31°C, 73.8 bar), safety (non-toxic, non-flammable), low cost and high availability (by-product produced in large volume from different sources) [25]. Synthetic fibers, in particular polyester, are perfectly compatible with supercritical carbon dioxide (scCO₂) and the respective scCO₂ dyeing process was commercialized by DyeCoo in 2012. In a typical setting, solution of a dye in scCO₂ is pumped through a roll of textile at high temperature and pressure (80–120°C and 200–250 bar) until dye absorption is complete. Evaporation of scCO₂ gives dry textile and dye leftovers in a separate vessel. Environmental benefits are 40–60 l/kg water savings, 0.2–0.3 kg/kg process chemical savings, smaller dye leftovers (1% vs 10% for water) and lower energy consumption. Additionally, scCO₂ dyeing allows freedom in factory location since it is not reliant on water sources and has lower machine operational costs.

However, dyeing of natural fibers is more complicated. While scCO₂ is a good solvent for dyeing polyester (hydrophobic solvent and substrate), water is a good solvent for dyeing natural fibers (hydrophilic solvent and substrate) [26]. In contrast to polyester, scCO₂ does not promote swelling and plasticization of natural fibers, and dyes do not readily diffuse into them. Cotton is an especially challenging substrate due to a hydrogen-bonded cross-linked framework which remains nearly intact in scCO₂. Therefore, either natural fibers must be modified for the dye to adhere to the fabric, or process chemicals must be added to promote dye uptake. Fiber modifications in their present state seem too chemicals-intensive for an eco-friendly solution and also require an additional water-based pre-treatment step. Medium modifications hold considerable

promise, but a feasibility study is needed to find out to what extent environmental benefits of scCO₂ dyeing will be preserved. While the dyeing itself can still be more energy-efficient (comparable dyeing conditions, for example), recycling of process chemicals raises some concerns. Main implementation barriers are the same as for other supercritical fluid technology applications, and are associated with high equipment price compared to traditional setup. More specifically with respect to natural fibers, studies are needed to confirm expected process benefits and the possibility to reach the desired dyeing quality at an acceptable environmental cost.

3 Discussion

Building on prior published work [14]–[16], this section presents the issues emerging in the industrial pilots by categorizing them and suggesting ways to overcome the barriers encountered. The pilots connecting to each barrier are annotated as numbered superscripts in **Table 1** for engineering challenges, **Table 2** for business challenges, and **Table 3** for other legal and societal challenges.

Table 1. Barriers and recommendations from an engineering perspective.

Barriers	Recommendations
The material heterogeneity and contamination make it difficult to reprocess ¹	Avoid mixing incompatible materials and establish standards to define “sustainable” composite materials
The technology or processes for separation, decontamination, recycling and/or reprocessing do not exist due to lack of R&D ^{1,2,3}	Create a strong research community for scientific and technical development to explore solutions for material reprocessing
Recovery solutions exist but are not widely available ^{1,2,3}	Deploy recovery solutions and the necessary infrastructure to ensure accessibility
The recycled material does not have the characteristics (aesthetic value, quality or performance) required for its reuse ¹	Ensure that reprocessing does not degrade the material quality, that the material properties are known and stable to enable reuse in new products
The processes for material reprocessing is too complex or too inefficient to be attractive ^{1,2,3}	Develop materials which can be reprocessed with minimal mechanical, thermal and chemical treatment
The complexity of the component (its structure and assembly) makes it difficult to repair and disassemble ^{1,2}	Design products and components for longevity, non-destructive disassembly, reparability and remanufacturability
The materials are difficult to transport and store (e.g. time-sensitive, condition-critical, voluminous, needs monitoring) ^{1,2}	Develop storage solutions and local reprocessing infrastructure
The material is hazardous with adverse health and environmental effects ^{1,3}	Engineer materials which are inert or non-toxic when handled adequately so they can be reprocessed safely
The resources required and environmental impacts generated by recovery processes offset in part or completely the benefits (compared to linear disposal) ^{2,3}	Evaluate the potential environmental trade-offs in the waste management system and develop alternative solutions to increase the net benefits of recovery

Table 2. Barriers and recommendations from a business perspective.

Barriers	Recommendations
<i>Economic viability</i>	
Virgin materials are cheap and abundant resulting in low incentives for recovery despite high “environmental and social costs” ^{1,2}	Integrate externalities as an economic cost (tax or penalty) to balance the economic competitiveness of sustainable alternatives
The inherent economic value of the end-of-life products, components or materials is insufficient to justify the investments required for their recovery ^{1,2}	Create a market pull (demand) for recycled materials to incentivize the development of adequate infrastructure for cost-efficient recovery and reprocessing of recycle
There is too much diversity in material composition and product design to allow for efficient and economically viable recovery ^{1,2}	Standardize key aspects of material, product and component design so the recovery solutions are applicable industry-wide and benefit from economies of scale
It is too difficult to evaluate and compare circular and linear solutions, especially considering returning material flows’ uncertainty ¹	Develop evaluation methods to highlight trade-offs between short- and long-term effects, thus better supporting decision makers
<i>Organizational context and governance</i>	
Top management does not integrate sustainability in the business strategy ^{1,3}	Prioritize sustainability as a core value in the business strategy
Top management is resistant to deviation from business-as-usual (risk aversion) which limits their ability to innovate ^{1,3}	Encourage green innovations and show willingness to change through top management commitment and support (CSR)
The company focuses on operating within a fixed model (high reliance on given constraints) ^{1,2,3}	Develop and test new ideas continuously to increase agility around constraints and build resilience capabilities to operate flexibly under uncertain conditions
<i>Industry stakeholders and value chain configurations</i>	
The current linear model of production and consumption is the norm in a given sector despite its environmental and social impacts ^{1,2,3}	Increase the visibility of impacts caused by the current linear model
There is no interest in shifting for CE and no awareness about the benefits of doing so ^{1,3}	Advocate for circular solutions by showcasing the benefits through examples of best practices relevant this sector
There are no clear responsibilities for handling the end-of-life materials ¹	Create a chain of responsibility and accountability for the impacts generated at each step of the supply chain by the actors with control over the materials
The materials and products are distributed and difficult to locate ^{1,2}	Define central locations for collection and inform relevant stakeholders
There is insufficient information sharing to develop efficient circular solutions ^{1,2}	Connect relevant stakeholders along the value chain to feedback information necessary for continuous improvement of material recovery processes
There are no established structures to develop the necessary industry-wide solutions for CE and the benefits of value recovery are distributed between stakeholders in ways that do not encourage investing in such infrastructure ^{1,2}	Promote collaboration to generate and share benefits with all stakeholders involved in the circular value chain

Table 3. Barriers and recommendations from a non-industrial stakeholder perspective.

Barriers	Recommendations
<i>Regulatory framework</i>	
There are no government incentives to tackle the problematic material flows ^{1,2}	Offer subsidies and support to stimulate the transition to CE
There are no consequences for wrongful handling and disposal of materials ^{1,2,3}	Impose substantial fines and strict control of wrongful handling and disposal of materials
Old regulations are preventing the shift to alternative waste management systems ¹	Remove regulatory barriers by adapting legal requirements to BAT
<i>Public perception and consumption habits</i>	
End-users/consumers are not aware of the problems caused by the current linear model and has accepted is as the status quo ^{1,2,3}	Educate end-users/consumers about the impacts of the current linear model and share examples of best practice to inspire change
There is no information available to end-users/consumers about the impact of product and materials life cycle to influence their purchase decision ^{1,2,3}	Increase transparency about the impact of product and materials provenance and end-of-life management through clear communication solutions (e.g. eco-labels)
There are no public discussions or media coverage about the disposal of problematic materials due to discomfort or taboo ^{1,2,3}	Raise public awareness and interest in tackling these issues through sensible communication media and sensible solutions

4 Conclusion

This paper presented three pilots exploring circular solutions within industrial systems. We discussed arising issues to extract lessons learnt based on the barriers encountered (technical, economic, organizational, structural, legal and societal). Some of the circular solutions explored make use of digital technologies (automation, information sharing, operator support, computer vision and machine learning). We also identified and evaluated trade-offs between achieving circular processes and reducing the net environmental impact of these processes. We went on to make recommendations to overcome the barriers identified. Some of the key messages are summarized below:

- Recovery processes are often too complex or too inefficient to be attractive when products and materials are not designed to fit in a CE. Product complexity (its structure and component assembly) makes it difficult to disassemble in a non-destructive manner. Efficient and automated reprocessing technologies are sometimes available or can be developed to overcome such barriers. However, integrating environmental considerations in early stages of the product design remains a priority.
- In some cases, the environmental impacts generated by circular processes offset some of the benefits compared to traditional processes and linear disposal. Trade-offs must be evaluated between the benefits and additional impacts of the waste management system. Alternative solutions must be explored to increase the net benefits of recovery and make them more attractive economically and environmentally.
- End-of-life materials or products can be difficult to transport and store. When adequate infrastructure and transport solutions are not in place, products may lose some of their value before reaching the stage where it can be recovered. This is especially

the case when the benefits of value recovery are distributed between stakeholders in ways that do not incentivize investments in such infrastructure. Collaboration across the supply chain is therefore necessary to promote value retention.

- When the materials and processes have adverse health and environmental effects, standardized procedures must be in place to ensure they are handled and reprocessed safely. Automation is often an attractive solution; however, material and product diversity hinder technical feasibility and economic viability. Key aspects of material, product and component design should be standardized so the recovery solutions can be applied industry-wide and benefit from economies of scale.
- Information sharing between end-of-life (recyclers and remanufacturers) and beginning-of-life stakeholders (designers and manufacturers) is often missing, thus limiting the ability to develop efficient circular solutions in the future. Relevant stakeholders along the value chain must be connected to feedback information necessary to develop circular solutions and to enable their continuous improvement. Such information flows can be supported by value chain digitalization; e.g. digital thread.
- When the recovery processes are handled by the original manufacturer, lack of information is less of an issue, although the product complexity and variability remain a challenge. The tasks require high levels of skills and knowledge; thus operator support and training (reskilling and upskilling) are needed. Digital solutions can provide an enabling platform for knowledge transfer and information flows to and from the process to support continuous improvement of circular processes.

Further work aims to implement the recommendations and scale up the solutions proposed to demonstrate their economic feasibility and environmental benefits, and showcase inspiring examples of circular industrial processes.

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