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Common challenges for circular manufacturing industries in recycling

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Abstract

Over the past two decades, the concept of the circular economy has undergone significant development. Notably, research efforts have been centered on key elements essential for the shift towards circularity, specifically the Value Retention Options (ROs), aimed at optimizing resource retention throughout product life cycles. Given the diverse application fields, these ROs have been conceptualized in various ways. Recycling is considered one of the key ROs impacting the end-of-life of products to reduce landfills. An analysis is presented focusing on recycling activities to highlight key challenges encountered by manufacturing industries and their transition towards circularity. Examples of application fields involved are used to support the analysis. The considered research helps bridge the gap between research priorities and industrial requirements, as it highlights the shared challenges confronted by application fields engaged in the longest loops of a circular economy.

Keywords: Circular economy; Value chain; Value retention options; Manufacturing; Recycling;

1. Introduction

In response to the pressing imperatives of waste management and the looming scarcity of essential virgin materials, industries worldwide are rapidly embracing circular value chain business models [2, 10]. The transition towards circularity embodies one of the defining challenges of modern times, signifying a transformative shift from the traditional linear approach to a regenerative and sustainable framework of the Circular Economy (CE). This profound realization has catalyzed a concerted drive in both academic and industrial circles to harness the potential of existing technologies and innovations to maximize resource efficiency and minimize waste. Furthermore, global policymakers such as the European Environmental Agency (EEA), Ellen MacArthur Foundation (EMF), World Economic Forum (WEF), and CE Club (CEC) are actively formulating sustainable and circular policies to underpin this transition. The confluence of these efforts underscores a collective determination to forge a more circular, restorative, and resilient future.

The concept of CE is based on three main principles: (1) eliminate waste and pollution. (2) circulate products and materials (at their highest value). and (3) regenerate the nature [34]. Guided by these principles, the EMF is dedicated to serving as a guideline for the transition to a circular value chain model for all stakeholders [9, 26, 34]. With the main objectives of sustainable development, such as biodiversity, business models, climate change, education, and finances the foundation addresses the range of industries involved in these endeavors encompassing the built environment, plastics, urban development, fashion, and food production. EMF's butterfly diagram visually illustrates the continuous material flow within a circular value chain [8]. This diagram highlights two primary cycles: the technical and biological cycles. In the context of industrial transition, the focus primarily rests on the technical cycle, which emphasizes the continuous circulation of products or materials utilizing Value Retention Options (ROs), where a RO is a *central common denominators spanning various academic fields and different types of studies, commonly operationalized in the form of a hierarchical 'R-ladder' or R-imperative [33].*

A range of frameworks concerning strategies based on ROs has been investigated in existing literature, ranging from the fundamental 3-ROs to the more intricate 11-ROs, adapting to specific topological requirements. Nevertheless, there has not been an observable shift in the progression from simpler methods like the 3Rs (Reduce, Reuse, Recycle) to more complex ty-

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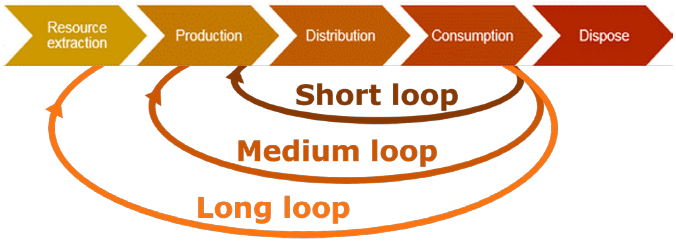

Fig. 1. Illustrative representation of short, medium and long loops in CE.

pologies like the 11Rs. Frequently, a hierarchy is established within these resource-oriented strategies, as they involve increasingly substantial levels of transformation applied to the product. Given these disparities, the ROs framework defined by [47] is opted to streamline the terminology and structure of this work. The framework developed by [47], categorizes ROs into three loops: short, medium, and long, as depicted in figure 1. In a short loop, the product remains in proximity to the consumer while retaining its original functionality. While in the medium loop, products are reprocessed to be upgraded by the producer. In a long loop, products lose their original function. The level of circularity descends from the short towards the long loop. In this study, the focus is on a long loop specifically the recycling process. Recycling is defined in [33] as *to transform the product or component into its basic materials or substances and reprocess them into new materials*. The recycling process intends to keep material flow within the circular value chain thus minimizing the waste. However, it is noteworthy that various application fields affiliated with adopting recycling in their journey of circularity encounter distinct challenges. The transitional challenges of the recycling process are application field-specific and vary with the nature of the value chain. In this work, the literature reviews on recycling and the challenges encountered by the different types of application fields are analyzed.

2. Related State of the art and contribution

In this section, an effort is made to explore the existing body of review papers concerning recycling along with the application fields within the circular value chain to analyze the evolving trends in this area.

2.1. Literature Review:

In the last decade, several reviews focused on the recycling of plastic materials. For instance, the review by [59] delves into the topic of bottle-to-bottle recycling of post-consumer polyethylene terephthalate (PET) packaging materials. Numerous reviews explore the up-cycling of plastic materials, encompassing diverse aspects such as the conversion of polymer waste into usable products and their recycling as raw materials [6], addressing challenges in polyurethane up-cycling [28], investigating PET bio-up-cycling with current bio-technologies [23], considering bio-up-cycling of multilayered plastic materials and blends [44], integrating 3D printing technology into plastic recycling [21], and exploring the creation of graphite nanocomposites from waste resources, with a particular focus on energy prospects [18]. In a separate strand of research, various reviews analyze plastic recycling practices geographically, such as [19] for South Korea and [16] for Australia. Reviews on recycling of plastic are diverse and cover many application fields

Many reviews were found while focusing on the application field of textile recycling, [46] provides a comprehensive review of state-of-the-art developments. [27] examined the up-cycling of textile waste while using pyrolysis. [57] reviewed end-of-life managements of footwear. Another application field discussed in the literature is electronics, in particular lithium-ion battery recycling. A literature review focusing on challenges opportunities and issues of recycling treatments for lithium-ion is presented by [40, 22, 14, 49]. The other application fields with review papers on recycling are construction field [7], recourse recycling [24, 58], and sustainable material recycling [18].

2.2. Paper contribution

The provided analysis of previous review papers on recycling highlights that existing literature predominantly concentrates on specific application fields and does not provide any common vision to guide manufacturing industries in their circular transition. This paper presents a detailed analysis of the literature on recycling to highlight key challenges encountered by manufacturing industries and their transition towards circularity by developing a common mapping of challenges among different application fields. This paper contributes by bridging the gap between research priorities and industrial requirements, as it highlights the shared challenges confronted by different application fields engaged in the longest loop of CE.

3. Recycling Analysis:

The analysis and the classification discussed in this paper include 35 references (31 journal articles and 4 publications on the proceedings of recognized international conferences) on recycling that have been published between 2005 and 2023 (80% in the last 5 years). Among the selected references four types of research streams are identified, detailed below. The criteria to analyze each stream is searching for the challenges and application fields in each stream. The objective is to map the challenges and application fields to find the possible synergies in a long loop.

3.1. Assessment of product impact

In the first identified steam, product impact assessment in the CE is carried out. Life cycle assessment (LCA), is a methodology used to evaluate the environmental impact of a product or service throughout its entire life cycle. [53], designed an optimum value chain, to find the best trade-off solution in the cradle-to-cradle life cycle for carrier bag alternatives which consist of either recyclable plastic or paper bags. [11] conducted an LCA to evaluate the use of polylactic acid (biodegradable and renewable) and PET (petroleum) in bottles for drinking water. [5] presented consequential LCA of a plastics de-polymerization technology, to assess the marginal LCA impacts of the European bottle-grade PET market. [41] employed LCA to model recycling processes for plastic containers and packaging, considering different resin compositions and recycling schemes. [50], carried out LCA to improve enzymatic PET to make recycling more environmentally friendly. The material flow analysis (MFA), is defined as a method of quantifying and assessing the flows and stocks of materials in a system, such as a city, a country, or a company [39]. To access the performance of the waste management system for municipality solid waste MSW recycling in Switzerland, [13] performed MFA by calculating the recycling rates. While [36] evaluated the performance of a large-scale material recovery facility by utilizing the developed datasets for the considered packaging facility. For Austria waste management [56] conducted quantitative and qualitative investigations of plastic packaging using MFA. [1] performed the MFA for plastic recycling of packaging material using the data collected from recycling and sorting plants of process efficiencies, material flows, and barriers. [37] performed the MFA of plastic flow in Trinidad and Tobago. [37] proposed a novel Li-Ion battery mechanical pretreatment for improved selectivity and pre-concentration of the output streams, so that the used material supplied to the battery production line is of the required quality. To improve the decision-making process like selection trade-offs and information collection for the domestic plastic waste generation [15] integrated digital technologies like geographic information systems and the global positioning system. For transformation of battery and buildings value chain enablers of circularity [30] compared the potential and re-requisite to the defined policies and legal frameworks.

3.2. End-of-Life (EOL)

The second stream in the literature identified is EOL, where after-life treatment of the recycled material problems are considered. [12] proposed a bill-of-material-based approach to determine the EOL strategy decision-making for sorting the components for either re-manufacturing, recycling, or reuse. [32], in their work incorporated sustainability and designer perception to determine the EOL options for an automobile gasoline engine. [52] developed a framework to assess the alternative processes for waste producers and resource consumers of the plastic PET recycling sector. [4] analyzed the current plastic waste management infrastructure and identified chemical additive releases through a material flow analysis. [25], developed an automation method for waste-sorting of medical waste.

3.3. Enablers towards circularity

The third stream identified in the literature addresses the transition of linear systems to circular value chains. [48] performed a qualitative study to explore the drivers, inhibitors, and enablers of creating textile-to-textile recycling systems for the Scandinavian fashion field. The authors identified that sorting and recycling technology can be improved with the use of digital technology. [17] presented a framework to explore new opportunities and challenges faced by companies in terms of competitive business advantage resulting from the redesign requirements of the supply chain. The authors considered four types of application fields transiting towards circular value chains fast-moving consumer goods retailers, healthcare, automobile manufacturers, and food-production corporations. [51], addressed the challenge of managing the information waste flow based on the integration of different manufacturing processes within the value chain. [43], identified the need for the availability and accessibility of information in the electronics sector. [38] developed a road map for the implementation of digital circular manufacturing and social life cycle assessments for the application fields of textile and cloth (TC) sectors. [42] explored the applicability potentials of digital innovations adopted by African entrepreneurs in the plastic value chain by considering recycled (thermal and mechanical) carbon fibers as an alternative raw material. Similarly, [35] demonstrated the feasibility of using recycled carbon fibers in thermoset-based composite applications using UV-assisted 3D printing technology.

3.4. Process design and optimization

The fourth stream identified is process design and optimization. Since the introduction of the CE, circularity-related process designs for the given product have been developed aiming mainly at closing the material loop intended for economic objectives and increasing material circularity for alleviating environmental objectives. [29] developed an approach for assessing the use of recycled material by developing the material circularity index, to assess the impact of the percentage variance of recycled material usage in PET bottles. [45] performed a study to observe the possible impact of repetitive circulation of PET to maximize the usage of recycled material for plastic bottle production before the degradation of the quality of the material. [3] considered the process design for PET used in packaging materials to improve the efficiency of recycled material by focusing on the enzymatic recycling process of the value chain. [54], designed a process for upcycling PET, by targeting the bio-recycling in the value chain. [55] conducted a process-based LCA focusing on enzymatic recycling of PET, to produce both terephthalic acid and ethylene glycol. [31] proposed a structure-based, machine-learning algorithm to engineer a robust and active PET hydrolase, to improve the quality. [20] developed a chemical recycling process while performing an impact assessment on the circular value chain, for plastic PET recycling.

4. Mapping challenges and application fields

In this section, the mapping of the challenges and application fields in each stream is presented as indicated in Table 1.

Research Streams	Application Fields	Challenges
Assessment of product impact	Municipal Fast moving consumer goods (Plastic) Textile (Plastic) Electrical and electronic equipment	Material selection Trade-off Computational complexity Recycling process Improvement Technological implementation Data Availability Data traceability Data verification Development of collection and sorting techniques, Recycled material improvement (quality + material recovery)
End of Life	Electrical and electronic equipment Automotive Medical Municipal (Plastic) Fast moving consumer goods (plastic)	Improvement in collection and sorting techniques Data Management Recycled material Improvement (quality + material recovery) Technological implementation
Enablers towards circularity	Electrical and electronic equipment, Automotive Medical Municipal Construction and demolition Fast moving consumer goods	Improvement in the recycling process and sorting techniques Data (Usage) Design innovations Recycled material improvement (Quality + material recovery) Project management Competency Assessment methods Logistic Legal framework (development+implimentation+improvement)
Process design optimization	Electrical and electronic equipment Fast moving consumer goods (Plastic) Municipal (Plastic)	Technological implementation Improvement in collection and sorting techniques Recycled material improvement (quality)

Table 1. Mapping of application fields and challenges

4.1. Assessment of product impact

In this stream, the main challenge is *material selection trade-off*. Normally the trade-off is either choosing a material that is more recyclable but has a higher environmental burden in its production or choosing a material that is less recyclable but has a lower environmental burden in its production. The *computational complexity* is another repetitive challenge in the literature mainly because of multiple scenario evaluation and the need for dynamic models. The other repetitive challenge is of *recycling process improvement*, where the recycling process is improved by using alternative types of recycling processes instead of conventional mechanical recycling. A stream of papers addresses the challenges related to the problem of waste management, where minimization of virgin material use and maximization of recycled material use are considered. These types of problems deal with resource transformation due to the complexity of the number of flows to manage, their potentially different nature and characterization, and the number of actors involved. Which makes the *technological implementation* a major challenge. The *availability of data* is a challenge in cases when most of the data on materials that flows through the resources, is incomplete or even unavailable. The *traceability of data* due to the value chain complexity is also a challenge. Lastly *data verification* is also considered a challenge due to multiple reasons, such as lack of transparency and standardization. In papers focusing on developing countries, the challenges are mostly related to the *development of collection and sorting techniques*. Another major challenge identified is *recycled material improvement* covered in the papers addressing the recycling sectors, mainly to address two types of challenges, (1) material recovery and (2) the quality of recycled materials.

For all the works selected in this Stream discussed above in section 3.1, belong to four application fields, **Muncipal, fast-moving consumer goods, textile and electrical, and electronic equipment.**

4.2. End-of-life

In this stream, *improvements in collection and sorting techniques* is the most addressed challenge. Another major challenge is *data management* because of the limited knowledge of the product at the design stage. The challenge of the *recycled materials improvements* exists in this stream as well, as detailed in the previous section 3.2. Here the challenge of *technological implementation* main focus is to improve the recycling process.

EOL literature detailed in 3.2 covers these application fields: **Electrical and electronic equipment, automotive, medical, municipal and fast moving consumer goods.**

4.3. Enablers towards circularity

This stream represents the wider scope of challenges and application fields (even in the same studies), keeping the focus on recycling the following challenges and application fields are identified respectively. *Improvement in the recycling process and sorting techniques* is considered one of the key challenges where the up-gradation of these processes is carried out.

In this stream, the challenge of *data use* is related to the problem of information waste. In *design innovation* challenges, innovative material design considerations are made to make processes like collections and collaboration more efficient. The challenge of *recycled materials improvement* exists for the development of new routes for the usage of recycled materials. The lacking parameters such as defining an appropriate scope, the absence of a standardized performance index, and the lack of universally accepted assessment methods, are mapped as challenges of *project management, competency, and logistic* respectively. Lastly, the challenges of *legal frameworks* are mapped according to development, implementation, and improvements depending on geographic research.

The works selected in this stream discussed above in section 3.3, belong to application fields of **electrical and electronic equipment, automotive, medical, municipal, construction and demolition, and fast moving consumer goods.**

4.4. Process design and optimization

The literature discussed in section 3.4 regarding process design mainly focused on addressing the financial and environmental objectives. The identified challenges are discussed below. One of the main challenge is of *technological implementation*, which is because of the process complexity of resource and information transformation, and the limited capabilities of collection facilities. Another challenge identified is *improvement of collection and sorting techniques*. Lastly, the challenge of *recycled materials improvement* in this stream is regards to the value addition process for conversion of recycled materials of the required quality. The works selected in this stream as discussed above in the section 3.4, belong to application fields of **electrical and electronic equipment, fast moving consumer goods, and municipal**

5. Conclusive remarks and future developments

The motivation of this work is to act as a bridge between academic research priorities and the practical needs of industries transitioning towards circularity. While emphasizing the crucial role of ROs, starting with recycling in the long loop of the value chain. An extensive literature review underscores challenges across different manufacturing industries is performed. Four main streams of literature are identified such as product impact assessment, EOL management, enablers for circularity, and process design optimization. Lastly, the application fields and challenges are mapped against each research stream respectively.

For future work, two possible aspects are:

1. This mapping can be used to elucidate the possible potential synergies between different manufacturing industries transiting towards circular value chains while regarding recycling.
2. Extending the common mapping of the challenges and application fields to the relevant research streams of the inner loops of the circular value chain, such as loops of repair, re-manufacturing, and re-use.

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