A comprehensive framework of circular economy practices for the manufacturing sector

Imadeddine OUBRAHIM* and Nathalie SAUER

Abstract— **This paper presents a comprehensive framework for identifying and structuring circular economy (CE) practices in the manufacturing sector, structured around the widely recognized 6Rs framework. The framework identifies twenty-three key CE practices based on the literature review, organized under these six categories. The paper provides a structured set of practices that can support future monitoring and assessment of CE initiatives in manufacturing companies. This framework offers a practical guide for decision-makers (DMs) to enhance sustainability, optimize resource efficiency, and foster circularity in manufacturing operations.**

Keywords—**Circular economy; CE practices; framework; manufacturing sector; sustainability assessment**

I. Introduction

The transition toward a CE has become a key priority for manufacturing companies seeking to enhance sustainability and reduce environmental impacts [1]. Traditional manufacturing systems mainly rely on a linear "take–make–dispose" model, which generates significant waste and depends heavily on raw material extraction [2]. As a result, manufacturing firms are increasingly adopting CE strategies to reduce resource consumption, extend product life cycles, and improve operational sustainability [3], [4].

In this context, CE adopts regenerative manufacturing systems through practices such as reducing material consumption, reusing products and materials, recycling waste, repairing products, remanufacturing components, and recovering valuable resources [5], [6]. These strategies are commonly conceptualized through the 6Rs framework: reduce, reuse, recycle, repair, remanufacture, and recover [7], [8]. Despite the increasing adoption of CE practices, manufacturing companies still face challenges in effectively implementing and evaluating CE practices. For example, organizations often face difficulties in systematically identifying and monitoring their CE practices [9]. Numerous studies have examined CE practices in manufacturing contexts [1], [4], [6], [7], [10], [11], [12], [13]. However, these studies have often focused on specific dimensions of circularity and a limited set of practices, rather than providing an integrated set of measures that adequately reflects the overall implementation of CE practices. This limits decision-makers' (DMs) ability to track progress, identify implementation gaps, and make well-informed strategic decisions. To fill this gap, the proposed paper develops a comprehensive framework of measures for CE practices in the manufacturing sector, structured around the 6Rs principles.

Imadeddine OUBRAHIM* is with the LGIPM research laboratory, University of Lorraine, Metz, France (corresponding author to provide e-mail: Imadeddine.oubrahim@univ-lorraine.fr).

Nathalie SAUER is with the LGIPM research laboratory, University of Lorraine, Metz, France (e-mail: Nathalie.sauer@univ-lorraine.fr).

Based on an in-depth literature review, the framework identifies twenty-three key practices that reflect core CE activities across manufacturing operations. A systematic organization of these practices into an integrated framework provides a conceptual foundation for understanding and supporting CE adoption within manufacturing firms.

The remainder of this paper is organized as follows. Section 2 presents the research questions and the methodology used to select and analyze the papers. Section 3 provides a structured literature analysis, including previous works on CE practices and their classification according to the 6R framework. Section 4 introduces the proposed framework of CE practices in manufacturing. Section 5 discusses the research implications and practical contributions of the framework, while Section 6 concludes the paper.

II. Materials and Methods

A. Research Questions

This paper aims to fill the gap found in the literature by defining a set of CE measures in a manufacturing context. This objective includes two research questions, which are examined in this article:

RQ1: Which CE practices in manufacturing can be used to assess CE adoption?

RQ2: How can these practices be systematically categorized under the 6Rs framework?

B. Methodology

The proposed framework has been developed by reviewing state-of-the-art CE and sustainability practices reported in the global literature over the last decade. Different databases have been considered to capture key sustainability and circular economy practices used for manufacturing operations purposes. These databases include Scopus and Web of Science. They have been chosen as bibliographical sources due to their widespread use and impact on the global academic community [14].

A well-structured methodology has been applied to select relevant manuscripts. The search strategy involved combining macro-topics in the databases, including ("measures" Or "Indicators" Or "practices" Or "Metric") And ("Circular economy" Or "CE" Or "Sustainability" Or "Triple Bottom Line" Or "TBL") And ("Manufacturing Sector" Or "Manufacturing Company" Or "Industry" Or "Firm" Or "Corporate" Or "Manufacturing" Or "Production"). Each applied filter progressively reduced the number of articles. Search terms have been chosen to capture measures, indicators, methods for selecting these CE practices, the concept of circularity, and the manufacturing context. After this analysis, the number of articles was 15309. The analysis has been further refined by applying several inclusion criteria. The search has been limited to publications from 2016 to 2026 and focused on relevant subject areas, including Environmental Science, Energy, Business, Management and Accounting, Computer Science, Decision Sciences, Economics, Econometrics and Finance, and Engineering. Additionally, only journal papers published in English were included. Subsequently, references from key selected papers have also been examined by reading and analyzing their titles and abstracts to ensure completeness, resulting in a final dataset of fifty-seven articles for detailed analysis. Figure 1 illustrates the different phases of the methodology process.

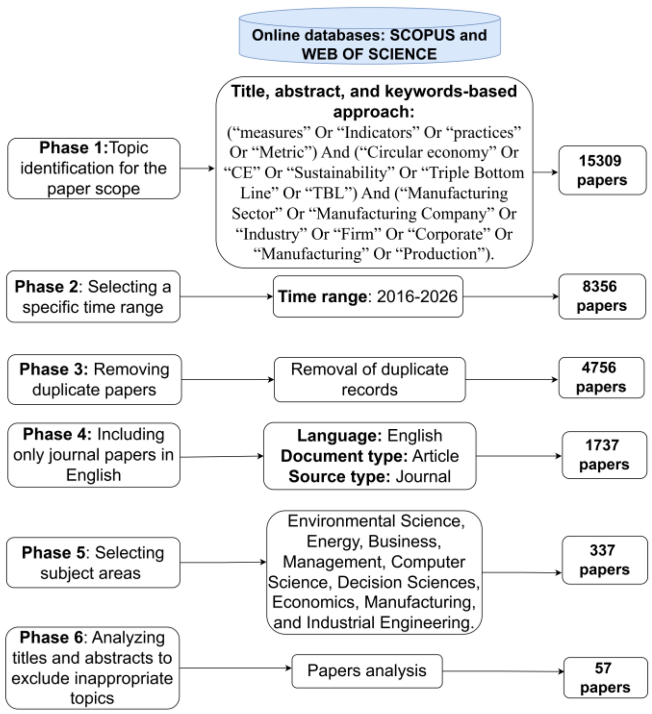

Figure 1. Flow diagram of the methodology process

III. Analysis of the Literature

In this section, a structured analysis has been conducted on papers that discuss the implementation of CE practices in the manufacturing sector. Based on the final dataset of 57 papers, the proposed research has focused on extracting relevant measures, indicators, and practices suggested in the literature to assess CE adoption. In the manufacturing context, CE practices are commonly structured around the 6R strategies, which include actions such as reducing resource inputs, reusing and recycling materials, recovering value from waste streams, redesigning products and processes, and remanufacturing systems to minimize raw material consumption, waste generation, and pollution while improving resource recovery and efficiency [15]. CE practices have been categorized according to the 6Rs framework: reduce, reuse, recycle, repair, remanufacture, and recover, as this classification provides a structured perspective on CE implementation and facilitates the organization of practices into a consistent analytical framework [7], [13].

A. Previous works on Circular economy practices

Numerous studies have examined CE practices in manufacturing settings. For example, [16] have proposed a conceptual framework that incorporates CE principles into manufacturing systems by linking product design, business models, and SC processes to improve resource efficiency and promote closed-loop material flows. Their findings show that, although environmental benefits are widely recognized, economic factors—especially long-term sustainability, competitiveness, and value creation—continue to be the main drivers of CE adoption. [17] have examined 114 CE definitions and discovered that most emphasize the 3Rs (reduce, reuse, and recycle), while the fourth R (recover) and waste hierarchies are seldom highlighted. They also identified a disconnect between sustainable development goals and current CE practices. [18] have analyzed the CE concept by evaluating its theoretical foundation and its application in policy and practice. They found that, despite CE being promoted as a sustainability solution, it has notable conceptual limitations and trade-offs. In another study, [19] have pinpointed major obstacles and opportunities for CE implementation in manufacturing, considering social-political, economic, legal, and environmental viewpoints. They created a structured survey questionnaire and distributed it to manufacturing companies in the UK and the EU. [20] have examined the main barriers to adopting CE practices in the Indian textile sector by reviewing existing literature and validating these barriers with industry and academic experts. They employed the DEMATEL technique to rank eleven key barriers and categorize them into cause-and-effect groups. Likewise, [21] have investigated barriers to adopting CE design strategies in mass timber construction through semi-structured interviews with industry specialists. Their findings revealed that these barriers impede the spread of CE design in mass timber projects and emphasized the need for regulatory reforms, demonstration initiatives, and capacity building to foster adoption. Finally, [22] have explored barriers to implementing CE practices within the manufacturing sector of the Gulf Cooperation Council region. They underscored the importance of coordinated policies, increased awareness, and capacity-building efforts to promote CE adoption and progress toward key sustainable development goals (SDGs).

B. Categorization of CE practices

Based on the analysis of the 57 selected papers, the extracted CE practices in the manufacturing sector have been systematically categorized under the 6Rs framework. The categorization allows for a structured perspective on CE implementation and facilitates the development of a comprehensive framework for assessing CE adoption.

- **Reduce (1R)**

The 1R dimension focuses on minimizing resource consumption and waste generation in manufacturing operations [12], [23]. It contributes to improving operational efficiency and reducing environmental impacts [4], [16], [24]. Key practices identified in the literature include reducing raw material consumption, minimizing waste generation, improving energy efficiency, and optimizing water usage [4], [5], [11], [14], [18], [26], [27], [28]. Manufacturing companies can also improve resource efficiency through process optimization and lean manufacturing approaches. [26], [29], [30]. The 1R strategy creates the foundation for implementing CE dimensions within manufacturing systems [31], [32], [33].

- **Reuse (2R)**

The 2R dimension emphasizes extending the utilization of products, components, and materials within manufacturing operations [8], [34]. It supports the retention of material value and reduces the need for virgin resources [35]. Previous works have highlighted key practices such as material repair and refurbishment, product return for reuse, and reused material quantity [36], [37]. In this way [38]. Furthermore, the 2R practices enable more efficient downstream CE strategies such as recycling and remanufacturing [37], [38]. [39]. This pinpoints the need to develop structured measures to monitor and evaluate the 2R performance, which can further support both operational efficiency and SDGs [31], [40].

- **Recycle (3R)**

The 3R dimension focuses on recovering materials from waste streams and reintegrating them into production processes [23], [41]. It helps manufacturing companies reduce waste disposal and improve resource efficiency [42], [43]. Previous works have revealed numerous key practices, including recycling manufacturing waste, collaboration for post-customer recycling, and integration of recycling into waste management systems [25], [44], [45]. Investment in recycling technologies and the integration of recycling into operational activities are also emphasized [15], [27], [46], [47]. Furthermore, the 3R practices support the transition toward circular manufacturing systems and downstream CE strategies [48].

- **Repair (4R)**

The 4R dimension aims to extend product lifespan through maintenance and repair activities [49]. It contributes to preserving product value and reducing product disposal within manufacturing systems [8], [48], [50]. Previous works have highlighted practices such as product repair operations, lifespan extension through repair, and preventive maintenance activities [8], [48], [49], [50]. The availability of spare parts and employee training in repair and maintenance are also important practices supporting CE implementation. Therefore, the 4R strategy acts as both a direct strategy to extend product life and an enabler for other CE strategies.

- **Remanufacturing (5R)**

The 5R dimension focuses on restoring used products and components to a like-new condition within manufacturing operations [51], [52]. It involves activities such as disassembly, inspection, repair, replacement of defective parts, and reassembly [51], [52], [53]. Previous works have reported product remanufacturing, integration of remanufacturing into operations, and investment in remanufacturing technologies as key CE practices [52], [53], [54]. The promotion of remanufactured products is also emphasized as an important strategy supporting circularity [54]. This highlights the need to develop crucial measures to monitor and evaluate 5R performance, which can further support both operational efficiency and SDGs.

- **Recover (6R)**

The 6R dimension emphasizes extracting value from waste streams through energy, materials, water, and resource recovery [1]. Previous works have identified practices such as energy recovery from waste, by-product recovery, and water and resource recovery systems [1], [53], [54]. Collaboration with SC partners for recovering resources from end-of-life products is also highlighted as an important CE practice [25]. In this regard, 6R practices support the reintegration of valuable resources into manufacturing systems and strengthen circular manufacturing operations [5], [56].

IV. A FRAMEWORK OF CIRCULAR ECONOMY PRACTICES IN MANUFACTURING

This section presents the proposed framework for CE practices derived from the literature analysis. The framework is structured around the 6Rs principles, which provide a comprehensive representation of circular strategies in manufacturing systems. A total of twenty-three measures have been identified and organized into these six categories to reflect key CE practices implemented across manufacturing operations. As shown in Figure 2, a conceptual framework maps the linear manufacturing flow, following raw material inputs through production and product use, and ends with waste generation. However, the 6Rs are positioned as interconnected loops that interact with different stages of the system. These interactions show how CE strategies can be applied to the production and consumption cycle to reduce resource use, extend product life, and reintroduce materials into the system. Therefore, the framework highlights the associations between the 6Rs and the manufacturing flow.

Based on the selected papers, a total of twenty-three

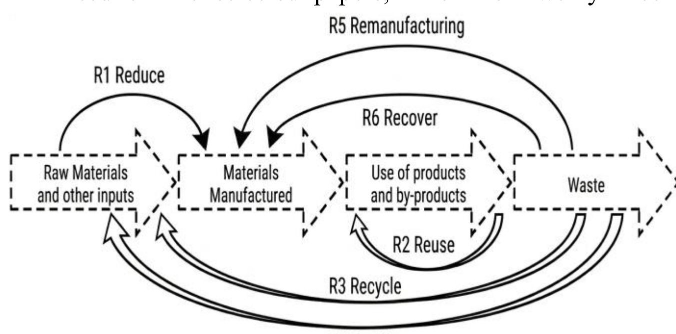

Figure 2. A conceptual representation of CE framework based on the 6Rs within the manufacturing flow

measures and practices have been identified and grouped into 6Rs categories to reflect the key CE practices implemented across manufacturing operations. These measures and practices are expressed as noun phrases, which allows for clear implementation and potential quantification in empirical studies.

Aside from the above, the 1R dimension emphasizes minimizing raw material (CEP1), energy (CEP2), water consumption (CEP3), and waste generation (CEP4), highlighting efficiency at early production stages. 2R and 3R strategies focus on the continued utilization of materials through practices such as material repair and refurbishment (CEP5), product return for reuse (CEP6), and reused material quantity tracking (CEP7), recycling of manufacturing waste (CEP8), collaboration for post-customer product recycling (CEP9), integration of recycling within waste management systems (CEP10), and investment in recycling efficiency technologies (CEP11). This indicates the importance of monitoring and managing material circulation within manufacturing operations, and also the role of both internal systems and external collaboration in improving recycling performance. Furthermore, 4R and 5R strategies aim to extend product life through product repair practices (CEP12), lifespan extension through repair (CEP13), spare parts availability (CEP14), and employee training in repair and maintenance (CEP15), as well as product remanufacturing (CEP16), integration of remanufacturing into operational processes (CEP17), investment in remanufacturing technologies (CEP18), and promotion of remanufactured products (CEP19). This highlights organizational capabilities required to support product longevity. Finally, the 6R dimension emphasizes the capture of residual value through energy recovery from waste (CEP20), by-product recovery (CEP21), water and resource recovery (CEP22), and prioritizing recovery over disposal (CEP23), thereby mitigating environmental impact. The identified CE measures and practices organized under the 6Rs dimensions are presented in Table I. The table illustrates both the extent of CE strategies in manufacturing and areas where practices could be further integrated or systematically measured.

TABLE I. A framework of CE practices organized by the 6Rs dimensions

Dimensions (6Rs)	**Code**	**Measure/Practice**	**Reference**
Reduce (1R)	CEP1	Raw material consumption reduction	[8], [12], [23], [26], [36]
	CEP2	Waste generation reduction	[10], [12], [26], [44], [52]
	CEP3	Energy consumption minimization	[1], [5], [12], [28], [56]
	CEP4	Water consumption minimization	[8], [24], [25], [26], [36]
Reuse (2R)	CEP5	Material repair and refurbishment	[7], [8], [25], [34], [37]
	CEP6	Product return for reuse	[7], [8], [25], [34], [37]
	CEP7	Reused material quantity tracking	[25], [35], [38], [55]
Recycle (3R)	CEP8	Recycling of manufacturing waste	[5], [12], [25], [38], [55]
	CEP9	Post-customer product recycling collaboration	[5], [8], [25], [25], [57]
	CEP10	Recycling integration in waste management systems	[5], [8], [25], [52], [57]
	CEP11	Investment in recycling efficiency technologies	[5], [25], [36], [51], [57]
Repair (4R)	CEP12	Product repair practices	[5], [25], [48], [50]
	CEP13	Product lifespan extension through repair	[5], [25], [48], [50]
	CEP14	Availability of spare parts	[25], [48], [50], [57]
	CEP15	Employee training in repair and maintenance	[5], [48], [50], [55]
Remanufacturing (5R)	CEP16	Product remanufacturing	[25], [51], [52], [54]
	CEP17	Integration of remanufacturing in operations processes	[36], [51], [52], [54], [56]
	CEP18	Investment in remanufacturing technology	[25], [51], [52], [54]
	CEP19	Promotion of remanufactured products	[36], [51], [52], [54], [56]
Recover (6R)	CEP20	Energy recovery from waste	[1], [5], [13], [52], [56]
	CEP21	By-product recovery	[1], [13], [25], [36], [55]
	CEP22	Water and resource recovery	[7], [8], [13], [25], [36]
	CEP23	Prioritization of recovery over disposal	[5], [8], [13], [26], [36]

V. DISCUSSION AND RESEARCH IMPLICATIONS

The proposed 6R-based framework provides a structured perspective on CE implementation in manufacturing operations. The distribution of the twenty-three CE practices across the 6Rs dimensions highlights the multidimensional nature of CE implementation in manufacturing operations, including resource efficiency, material circulation, product longevity, remanufacturing, and resource recovery. The proposed organization of twenty-three CE practices under the 6Rs framework enables DMs to evaluate CE implementation, identify gaps, prioritize improvement opportunities, and monitor CE adoption across manufacturing operations. The 1R strategies primarily focus on early-stage resource efficiency through minimizing raw material, energy, and water consumption, along with reducing waste generation. These practices establish the foundation for circular manufacturing operations through reduced resource consumption and lower environmental impacts. In contrast, the 2R and 3R dimensions emphasize the continued utilization of materials and products within manufacturing systems. The 2R practices include material refurbishment, product return, and reused material tracking, while the 3R practices involve recycling systems, post-customer recycling collaboration, and investment in recycling technologies. Furthermore, the 4R and 5R dimensions focus on product longevity through repair, maintenance, spare parts availability, employee training, and remanufacturing activities. These practices support product value retention and strengthen circular manufacturing operations. Finally, the 6R dimension emphasizes energy, by-product, and water recovery while prioritizing recovery over disposal.

The framework offers several practical implications for manufacturing decision-makers. First, it provides a structured tool to systematically assess CE adoption and identify gaps in implementation. Second, it highlights opportunities for strategic investment, such as in recycling and remanufacturing technologies, employee training, and recovery systems. Third, it emphasizes the importance of integrating internal practices with external stakeholder engagement, including supply chain partners and customers, to enhance material circulation and overall circularity.

From a research perspective, the proposed framework provides a basis for future empirical studies and quantitative

CE assessment models in manufacturing environments. Future studies may investigate the interactions among the 6Rs and their influence on sustainability performance. Despite its contributions, this study remains theoretical and relies on the existing literature, as the proposed framework has not yet been empirically validated in real-world industrial settings. Consequently, future research should focus on validating the proposed framework and developing approaches based on key performance indicators (KPIs) to evaluate the implementation and outcomes of circular economy initiatives.

VI. CONCLUSION

This paper proposes a comprehensive framework of CE practices for the manufacturing sector, grounded in the 6Rs framework. Based on a systematic review of fifty-seven studies, twenty-three CE practices were identified, including resource consumption reduction, waste minimization, material repair and refurbishment, recycling of manufacturing and post-customer waste, remanufacturing, and recovery of energy, water, and by-products. These practices can be systematically categorized under the 6Rs to provide a structured perspective on CE implementation, facilitating the monitoring, evaluation, and management of circular strategies in manufacturing operations. The framework serves as a conceptual and structured reference that can support DMs in understanding and organizing CE practices, enabling them to assess CE adoption, identify gaps, prioritize improvement areas, invest strategically in technologies and processes, and track progress over time. By linking specific practices to measurable outcomes, it supports operational efficiency, product longevity, and resource recovery, while also providing a foundation for benchmarking and comparative studies across industries. Although the proposed framework provides a structured conceptual basis for CE implementation in manufacturing, future studies should empirically validate the framework through industrial case studies and develop quantitative KPI-based assessment and scoring systems.

Overall, the proposed 6R-based framework integrates theoretical insights with actionable guidance, helping firms embed circularity into operations, optimize resource use, and advance sustainability performance, thereby addressing the research questions on CE practices, their categorization, and their practical evaluation in manufacturing contexts.

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