



Prioritizing Circular Economy actions for the decarbonization of manufacturing companies: the C-Readiness tool[☆]

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ABSTRACT

Climate change is pushing manufacturing companies to adopt sustainable solutions for reducing their carbon emissions. Circular Economy emerged as a suitable strategy for the decarbonization of industrial organizations, offering the potential to decouple economic growth from natural resource extraction and waste generation. However, achieving circularity requires significant transformation in several areas, and some Circular Economy actions may be more effective than others in reducing carbon emissions, depending on the product and company carbon footprint structure. Facing low awareness and limited resources, manufacturing companies frequently fail in understanding where to start in approaching such a systemic transition. Despite these challenges, the literature overlooks the linkages between Circular Economy initiatives and their potential for reducing carbon emissions, and in particular how Circular Economy actions can be prioritized for decarbonization purposes. To fill these gaps, this paper develops an original and systemic tool (C-Readiness) for assessing the readiness of manufacturing companies for the Circular Economy, and for prioritizing Circular Economy actions for decarbonization. The tool is developed based on a literature review and critical comparison of existing tools for assessing circularity readiness at the micro level. The tool has been applied to four manufacturing companies, to showcase its potential in designing Circular Economy-based decarbonization paths. This paper contributes to the literature on strategic Circular Economy implementation in manufacturing companies by integrating circularity readiness evaluations with quantitative carbon footprint assessments. It provides a structured approach and a simple yet effective tool to help industrial organizations reduce their environmental impact through Circular Economy practices.

1. Introduction

Climate change and the need to mitigate global warming are pushing manufacturing companies to contain and reduce carbon emissions (Dalla Longa et al., 2022; IPCC, 2023). According to the latest United Nations Emissions Gap Report, these emissions globally set the new record of 57.1 Gt CO₂e in 2023, with an increase of 1.3% from 2022 levels (UNEP, 2024). The manufacturing industry is a significant contributor to these emissions: in 2023, carbon emissions from the manufacturing sector accounted for nearly one-quarter of the total (UNEP, 2024). These emissions drive climate change and potentially cause long-term, irreversible, and self-perpetuating changes to planetary systems including hot temperature extremes, heavy precipitations, agricultural droughts, sea level rise from collapsing ice sheets, and ecosystem disruption (WEF, 2024). Therefore, there is the urgent need

for manufacturing companies to decarbonize their operations through carbon emissions reduction (UNEP, 2024). The adoption of Circular Economy, which offers the opportunity to decouple economic growth from natural resource consumption and waste generation, can be seen as an opportunity to reduce the carbon emissions of the manufacturing industry (Ellen MacArthur Foundation, 2019). However, transitioning to a Circular Economy requires fundamental changes in product design, production processes, business models, and supply chains, making it a complex and challenging task for manufacturing companies (Bressanelli et al., 2019; Das et al., 2024; Elia et al., 2020; Upadhyay et al., 2023). Faced with low awareness and limited resources, manufacturing companies at a preliminary evaluation stage of Circular Economy implementation frequently fail in understanding where to start in approaching such a systemic transition (Pigosso & McAloone, 2021). Various methods and tools have been proposed in literature to assist

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manufacturing companies and organizations in approaching this transition (Valls-Val et al., 2022). These methods often start with an assessment of the readiness of an organization to the Circular Economy, providing an initial snapshot of its circularity level. Nonetheless, there is still no agreement on which elements and circularity criteria should be used to assess the readiness of manufacturing organizations for the Circular Economy (Camacho-Otero & Ordoñez, 2017; Thorley et al., 2022; Vinante et al., 2021). Some tools neglect supply chain aspects (Baumer-Cardoso et al., 2023; Evans & Bocken, 2014) or circularity opportunities in company culture and green habits (Cayzer et al., 2017; Gusmerotti et al., 2019). Overall, the number and type of evaluation elements adopted largely differ, and the complexity of the Circular Economy paradigm is still far from being fully comprehended by existing instruments (Chrispim et al., 2023; Helander et al., 2019; Saidani et al., 2017).

On the other hand, Circular Economy initiatives may lead to a reduction of carbon emissions, but this does not occur automatically (Zink & Geyer, 2017). In particular, some Circular Economy actions may be more effective than others in reducing carbon emissions, depending on the product and company carbon footprint structure (Bressanelli et al., 2024). For instance, a company whose products end up in landfill may decide to start a Circular Economy project to reuse them, thus increasing their circularity. However, these products may consume energy during the usage phase. If the usage phase is the major contributor to the overall lifecycle carbon emissions of these products, reusing old products may be less effective for decarbonization purposes than other strategies such as product redesign for energy efficiency (Bressanelli et al., 2024; Iraldo et al., 2017). Therefore, companies at a preliminary evaluation stage should both consider their Circular Economy readiness level and the decarbonization potential of Circular Economy actions, in order to prioritize them when dealing with limited resources. However, current Circular Economy tools overlook the crucial aspect of decarbonization of manufacturing companies when designing strategic Circular Economy implementation roadmaps. Thus, they fail to provide adequate guidance on the prioritization of strategies that integrate Circular Economy principles with a potential reduction in carbon emissions, thereby giving little support in understanding how Circular Economy can be introduced in industrial organizations for decarbonization purposes. Therefore, the following Research Question is formulated:

RQ: How can companies strategically prioritize Circular Economy actions for decarbonization purposes at a preliminary evaluation stage?

To address this Research Question, this paper develops a new tool (called C-Readiness) for assessing the readiness of manufacturing companies for the Circular Economy and for prioritizing Circular Economy actions for decarbonization purposes. The tool has been developed based on a literature review and critical comparison of existing tools for measuring circularity at the micro level. Then, a case study methodology has been adopted for testing the tool in different settings and showcasing its potential. Applying the tool to four manufacturing companies allowed assessing their Circular Economy readiness and prioritizing Circular Economy actions based on their carbon emissions reduction potential.

This research advances the literature on Circular Economy implementation in manufacturing companies since the proposed C-Readiness tool is not limited to the assessment of the circularity level of manufacturing organizations, but it also provides indications on which Circular Economy areas of action should be prioritized to maximize the effects on company decarbonization. The novelty of the tool stands in the combination of circularity readiness evaluations with quantitative Life Cycle Assessment (LCA) methodologies to identify and prioritize Circular Economy implementation actions. Thanks to C-Readiness it becomes apparent that, to reduce carbon emissions, manufacturing companies should prioritize investments in different Circular Economy areas of action depending not only on their readiness profile, but also on

the carbon footprint structure of their representative products. By operationalizing this theoretical concept into the C-Readiness tool, this article adds fresh knowledge about Circular Economy implementation in manufacturing companies for decarbonization purposes and provides a useful tool to support investment decisions of manufacturing companies in a preliminary circularity evaluation stage.

The remainder of the paper is structured as follows. Section 2 provides the background of the research, describing how Circular Economy actions can be implemented in manufacturing companies for decarbonization purposes. Section 3 presents the multi-step methodology of this research. Section 4 presents the results, which include the review and critical comparison of existing tools that measure the readiness of manufacturing companies for the Circular Economy (Section 4.1), the development of the C-Readiness tool (Section 4.2), and its application to four case studies (Section 4.3). Section 5 discusses the results against the literature on Circular Economy implementation in manufacturing companies. Lastly, concluding remarks, managerial implications, limitations, and suggestions for future research are presented in Section 6.

2. Background: Circular Economy actions for the decarbonization of manufacturing companies

Circular Economy emerged as a sustainable alternative to the traditional production and consumption paradigm based on the *take-make-dispose* principle (Ellen MacArthur Foundation, 2019). It aims to overcome the limitations of a linear economy, since it decouples economic growth from natural resources exploitation and waste generation (Corona et al., 2019). The implementation of Circular Economy actions can occur at three different levels (Ghisellini et al., 2016; Moraga et al., 2019; Nikolaou & Tsagarakis, 2021). At the macro level, Circular Economy implementation addresses systemic and policy aspects. It involves government bodies, regulatory authorities, and policymakers that implement supportive policies and frameworks to accelerate this transition. At the meso level, Circular Economy implementation involves collaboration among multiple stakeholders (including suppliers, clients, and competitors) within a specific industry or sector to develop shared circularity goals and strategies. At the micro level, Circular Economy implementation focuses on individual companies and organizations (Kaipainen & Aarikka-Stenroos, 2022). It substitutes the end-of-life concept of products, components and materials with reduce strategies and closed-loop cycles of reuse, remanufacturing and recycling (Bressanelli et al., 2020; Konietzko et al., 2020).

Manufacturing companies and organizations that start implementing Circular Economy at the micro level can leverage on a set of actions, which entail the redesign of products, production processes, business models, and supply chains, adopting a life-cycle perspective (Bressanelli et al., 2021; Hansen & Revellio, 2020; Schöggel et al., 2023). First, the design of products should be modified to increase their characteristics of durability and disassemble-ability, as well as to encourage the adoption of recycled and bio-based materials in the production of new goods (Batista et al., 2023; Bovea & Pérez-Belis, 2018). The purpose of circular product redesign is to increase the effectiveness of end-of-life activities, including the separation of the various components and materials that can be sent for remanufacturing and recycling. Second, green production practices should be adopted in production processes, in a way to reduce their environmental impact by minimizing waste, pollution, and resource consumption (Cherrafi et al., 2021; González Chávez et al., 2019). They involve the adoption of various strategies and technologies to minimize the generation of waste and emissions, optimize the use of resources – including water and energy – and exploit the opportunities of industrial symbiosis for the exchange of by-products within eco-industrial districts (Fraccascia & Yazan, 2018; Mirlletz et al., 2024; Prieto-Sandoval et al., 2018). Third, organizations should rethink their business models, i.e., the way in which they propose, create, and deliver value to stakeholders (Geissdoerfer et al., 2020). In fact, products designed to last are incompatible with traditional revenue mechanisms

based on buying and selling (Stahel, 2016). Shifting business models to include product-service systems offering like leasing, pay-per-use and sharing is therefore needed, to avoid lost sales and cannibalization (Bressanelli et al., 2019). Thanks to these business models it becomes possible to satisfy the same demand level with a lower number of products in use. Moreover, in circular business models, product ownership remains with the supplier, who is therefore naturally incentivized to design products that last, to offer maintenance and repair services as well as to collect products at the end-of-life for reuse, remanufacturing, and recycling (Teigiserova et al., 2023). Fourth, a reconfiguration of the supply chain is needed, to select suppliers based on their environmental performances and to optimize the sourcing of materials and the distribution of products in a way to reduce transportation emissions (Agrawal et al., 2023; Belhadi et al., 2022; James et al., 2023). In addition, new forms of collaboration with all the players of a circular ecosystem should be explored (Konietzko et al., 2020; Marques-McEwan et al., 2023; Saccani et al., 2023). Fifth, manufacturing companies should implement regeneration activities and reverse logistics systems to manage the end-of-life of their products, in order to increase reuse, remanufacture components, and recycle materials (Garza-Reyes, Kumar, et al., 2019). Lastly, a ‘green culture’ and related habits should be developed within companies to facilitate the implementation of Circular Economy, such as by raising awareness among internal and external stakeholders and by adopting green marketing practices and external communication (Gusmerotti et al., 2019; Ki et al., 2023; Papamichael et al., 2023).

Implementing Circular Economy actions at the micro level can play a crucial role also in the decarbonization of manufacturing companies (Gallego-Schmid et al., 2020; Mirlletz et al., 2024). Decarbonization is the reduction and removal of greenhouse gases from the atmosphere (McKinsey & Company, 2024). As an example, extending the lifespan of products by design decreases the demand for new materials, which in turn reduces the carbon emissions associated with their resources extraction processes (Bakker et al., 2014; Marini et al., 2024). To evaluate the decarbonization potential of Circular Economy actions, quantitative methodologies based on the LCA methodology can be employed and combined with circularity evaluations (Hackenhaar et al., 2024; Rigamonti & Mancini, 2021). The LCA methodology is used to evaluate the environmental impacts of products throughout their entire life cycle (ISO 14040, 2021; ISO 14044, 2021). While LCA considers a range of different environmental impacts, the carbon footprint specifically focuses on quantifying and assessing the greenhouse gas emissions associated with the life cycle of a product (ISO 14067, 2018), measuring the amount of carbon dioxide equivalent emissions released into the atmosphere as a result of the product manufacturing, use, and disposal. Product carbon footprints thus help identifying the contribution of a product to climate change in different life cycle stages, such as the extraction of raw materials, production processes, transportation and distribution, usage, and end of life.

Overall, manufacturing companies can implement several actions to kickstart their transition towards a Circular Economy for decarbonization purposes. Adopting a systemic approach in this regard is critical (Bressanelli et al., 2021), since considering all these actions across the entire product life cycle and throughout the value chain avoids environmental burden shifting and prevents rebound effects (Bressanelli et al., 2024; Castro et al., 2022; Rigamonti & Mancini, 2021). However, it is usually not possible to undertake all these actions simultaneously, especially given resources constraints faced by companies (Pigozzo & McAloone, 2021). Therefore, it is essential to prioritize the actions to be undertaken, especially at a preliminary evaluation stage (Barros et al., 2023; Kristensen & Mosgaard, 2020; Marrucci et al., 2019; Roos Lindgreen et al., 2020; Walker et al., 2021). The impact magnitude of a Circular Economy action for decarbonization purposes depends on both (i.) how much the company has already invested in the past in the domain impacted by the action (i.e., its Circular Economy readiness); and (ii) the amount of carbon emissions that are generated in the

product life cycle stage where this Circular Economy action typically acts. The lower the readiness of a Circular Economy action, the higher its implementation potential. The greater the carbon footprint impact of the product life cycle stage impacted by the action, the higher its decarbonization potential. By combining Circular Economy readiness evaluations with carbon footprint assessments, manufacturing companies can prioritize investment decision on Circular Economy actions with a low readiness profile and that address a life cycle stage generating high carbon emissions. In contrast with this picture, the scientific literature interest in developing tools and methods for measuring the circularity readiness of manufacturing companies is recent (Baratsas et al., 2022; Kalmykova et al., 2018; Sherwood et al., 2022; Valls-Val et al., 2022), and current attempts primarily focus on assessing a company preparedness for the transition to Circular Economy, overlooking the crucial aspect of decarbonization. They thus fail to provide adequate guidance on the prioritization of Circular Economy actions to reduce carbon emissions. Consequently, manufacturing companies may overlook the potential synergies between Circular Economy and decarbonization, leading to suboptimal decision-making in their sustainability efforts.

3. Methodology

This study adopts a multi-method approach that combines literature review, conceptual development, and case studies (Fig. 1).

3.1. Literature review

A literature review and critical comparison of existing tools aimed at assessing the readiness of manufacturing companies for the Circular Economy has been performed. This process involved conducting a literature search to identify relevant tools for measuring circularity readiness and performance at a firm level, on a scientific basis. The literature identification, screening, eligibility and inclusion steps were inspired by the PRISMA methodology (Moher et al., 2009). To identify relevant studies, the following sets of keywords were combined in the Scopus database¹: (i.) “Circular Economy”, to delineate the context of the investigation; (ii.) “Readiness” or “Metrics” or “Measurement” or “Level of implementation” or “Circularity performance”, to define the main topic of investigation; (iii.) “Manufacturing” or “Industry” or “Firm level”, to set the scope, i.e., the boundaries of the Circular Economy readiness investigation at the micro, manufacturing level; (iv.) “Tool” or “Toolkit” or “Index” or “Prototype” or “Questionnaire-based” or “Method” or “Model”, to define the methodology behind the measurement of the readiness. This step, first performed in January 2024 and then updated in October 2024, led to the identification of 457 papers. To ensure the rigor and the quality of the identified contributions, only journal publications were kept for the screening step. Thus, 97 conference proceedings and book chapters were discarded. A total of 360 papers were screened by reading the title and abstract. Inclusion criteria for eligibility were set based on the aim of the tool (‘assess the readiness of manufacturing companies for the Circular Economy’) and on the actual description in the paper of a tool that allows companies to do such assessment. Many papers were discarded at this step because they addressed the topic only at a conceptual level, thus failing in providing a practical tool for such assessment. As a result, 18 papers were selected for full text analysis. By reading the full text, we found that the same tool was described or applied in more than one publication. Thus, 7 tools

¹ The full search string is: (TITLE-ABS-KEY ("Circular Economy") AND TITLE-ABS-KEY ("readiness" OR "metrics" OR "measurement" OR "level of implementation" OR "circularity performance") AND TITLE-ABS-KEY ("manufacturing" OR "industry" OR "firm level") AND TITLE-ABS-KEY ("tool" OR "toolkit" OR "index" OR "prototype" OR "questionnaire-based" OR "method" OR "model")).

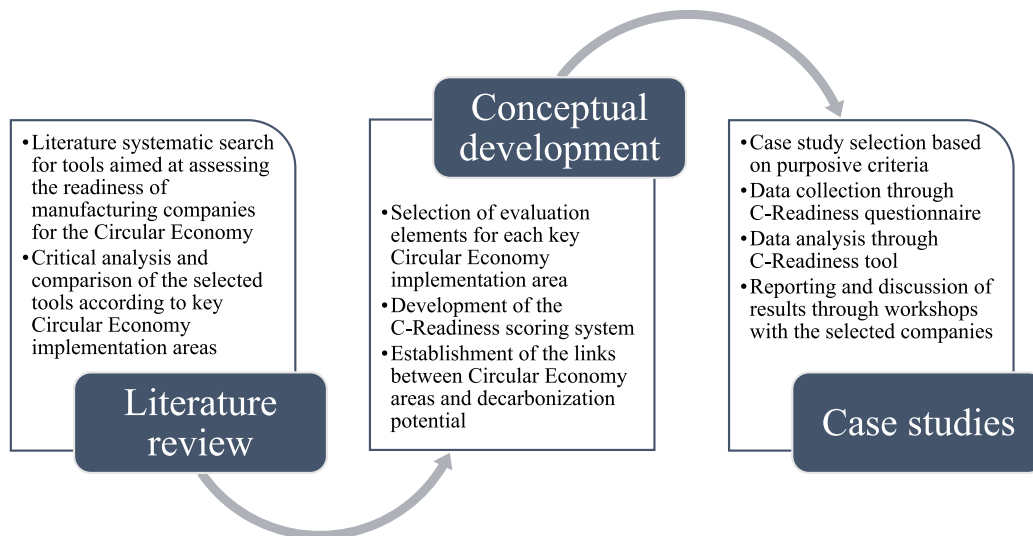


Fig. 1. Research design and methodology.

have been included for critical analysis and comparison, using the 18 papers as a source for the analysis. In addition, snowballing based on scientific literature that already reviewed available tools has been applied to complement the structured search (Baumer-Cardoso et al., 2023; Saidani et al., 2017; Valls-Val et al., 2022). Two additional tools, i. e., the Circular Economy Toolkit (Evans & Bocken, 2014) and Circulytics (Ellen MacArthur Foundation, 2020) were added at this step, being highly cited in the reviewed scientific literature (e.g. Baratsas et al., 2022; Pigosso & McAloone, 2021; Vinante et al., 2021). As a result, a total of 9 tools have been critically analyzed and compared based on their specific objective, scope, area and items of analysis, results calculation, and reported results (Section 4.1). In particular, for the critical analysis, each evaluation element used in the nine tools has been extracted and categorized based on the categories pointed out in Section 2. Therefore, 390 evaluation elements have been gathered and classified into one of the following areas: product structure, production process, business model, supply chain, regeneration, green culture and habits. The critical analysis allowed the comparison of the nine tools against the different key Circular Economy areas covered.

3.2. Conceptual development

The critical analysis carried out on the nine tools informed the subsequent step of the research, i.e., the conceptual development of the C-Readiness model. This model is intended to assess the readiness of manufacturing companies for the Circular Economy at a preliminary evaluation stage, and to prioritize Circular Economy actions for decarbonization purposes. After the categorization of the 390 evaluation elements in the six key Circular Economy implementation areas, duplicates and similar elements have been grouped by the researchers. For instance, the evaluation elements ‘use of recycled inputs’ (Evans & Bocken, 2014), ‘is the product made from recycled materials?’ (Cayzer et al., 2017), the ‘percentage of recycled raw materials out of total usage of raw materials’ (Gusmerotti et al., 2019), ‘to what extent is your company using recycled materials?’ (Pigosso & McAloone, 2021), ‘criteria for the use of recyclable material’ (Urain et al., 2022), and ‘indicator for the increased share of renewable material’ (Baumer-Cardoso et al., 2023), were all assigned to the first key Circular Economy implementation area (i.e., ‘product structure’), and grouped together under the first C-Readiness evaluation item that measures the extent to which the materials used in the product are recyclable or recycled. As a result, the number of evaluation elements for the new tool has been reduced from 390 to 33 items. This reduction in the number of

evaluation elements was pursued also to contain the complexity of the tool and keep compilation times short for companies (Amicarelli et al., 2023; Pigosso & McAloone, 2021). Then, evaluation elements have been converted into questions and a scoring system has been developed to gauge the level of Circular Economy readiness, based on a Likert scale. The links between Circular Economy key implementation areas and opportunities for decarbonization have been established, based on seminal scientific literature that attempted to merge Life Cycle Assessment (LCA) methods with circularity indicators (Brändström & Saidani, 2022; Gallo et al., 2023; Luthin et al., 2023; Marini et al., 2024; Rigamonti & Mancini, 2021). In particular, each organization is first asked to indicate a product that best represents their manufacturing company (e.g., a washing machine for a household appliances manufacturer), and to provide an estimate of the percentage distribution of this product carbon footprint along its typical life cycle stages (i.e., raw materials extraction, production processes, transportation and distribution, usage, end of life). This estimation can be gathered from a LCA study, if available to the organization; otherwise, generic LCA studies available in literature can be used. Then, each key Circular Economy implementation area has been assigned to the specific phase of the product lifecycle that would derive the greatest benefit from targeted Circular Economy investments. Lastly, the C-Readiness model has been implemented in a web-based platform to automate data collection and the reporting of results, and internally tested to verify its usability and effectiveness. The access to the C-Readiness tool is available upon request, while its screenshots are appended in the Appendix.

3.3. Case studies

The C-Readiness model has been tested and refined through case studies. Case selection was purposive. Selected companies are engaged in the production of physical, manufactured products and operate in different industries. The motivation for selecting these companies stems from their interest in carrying out a preliminary evaluation of their readiness level for the Circular Economy and in their awareness of the carbon footprint structure of their representative products. Four manufacturing companies were selected and then assessed through C-Readiness (Table 1).

Data collection followed the C-Readiness structure and was facilitated by the web-based platform. To ensure the representativeness of the results, data were collected from diverse individuals and organizational roles within each organization. This approach was adopted due to the multidisciplinary nature of Circular Economy and the fact that the

Table 1
Companies involved in the multiple case study.

	Company Alpha	Company Beta	Company Gamma	Company Delta
Industry and activities	Manufacturing of gas and fuels valves and accessories	Manufacturing of embroideries and decorations for fabrics and textile products	Manufacturing of professional coffee machines	Manufacturing of pallet wrappers
Turnover (€) (2023)	~ 165 million	~ 2 million	~ 135 million	~ 11 million
Number of employees (2023)	~ 400	~ 20	~ 300	~ 45
Number and role of people involved in the assessment	1 (Quality manager)	4 (CEO, Purchasing manager, Production manager, Administration and Finance)	4 (COO, Quality manager, Sales manager, R&D manager)	3 (CEO, Innovation manager, Sales director)

implementation of Circular Economy actions involves the transformation of different organizational areas. In particular, a first web-call was organized with the selected managers for each case company, to involve them in the C-Readiness evaluation and to show them how the tool works. Each evaluation element was explained in detail and time was reserved for asking any questions about terminology and contents of particular items. Managers were asked to fill in the instrument to the best of their knowledge. To not affect the results of the evaluation, they were asked to use the ‘don’t know / not applicable’ option if they were unsure of some particular answer. Feedback from managers was used to improve the understandability of the tool. For example, for some unclear terminology (e.g., industrial symbiosis), terminology explanation boxes with representative examples were added to the tool. Then, managers were requested to familiarize themselves with the web-based platform and to fill the tool with their answers within two weeks. Data analysis was carried out according to the C-Readiness structure to compute results through the lens of the different key Circular Economy implementation areas. Triangulation with secondary sources such as company websites, news articles and company dissemination reports improved the validity of results. Data has been analyzed within and across companies. To further validate the findings and gain deeper insights, final discussion workshops were conducted with the managers of the companies involved. During these workshops, the C-Readiness results have been presented and discussed with companies managers to identify and prioritize actions for decarbonization purposes, based on the results of the assessment.

4. Results

4.1. Review and critical comparison of tools that measure the readiness of manufacturing companies for the Circular Economy

Following the systematic literature selection process, 9 tools that measure the readiness of manufacturing companies for the Circular Economy have been identified and critically analyzed. They are listed in Table 2. The first tool was developed by Evans & Bocken (2014) in 2014. The authors developed the ‘Circular Economy Toolkit’ to assess a company products and services circularity and their potential enhancement. This tool employs 33 evaluation items, structured around seven areas of analysis that range from product design to manufacturing, usage, and end-of-life. Based on a set of pre-defined multiple-choice responses, the tool computes and returns a three-level (low-medium-high) improvement potential score for each assessed area and provides a list of suggestions on how to improve them. Cayzer et al. (2017) developed the ‘CEIP – Circular Economy Indicators Prototype’, a tool to measure and evaluate the performance of individual products against Circular Economy principles. It employs a questionnaire based on 15 evaluation items, grouped into five areas that follow the lifecycle of the product under evaluation. The tool qualitatively computes a final circularity score (0–100%) based on the provided answers, which can be further disaggregated for each assessed area. Garza-Reyes, Salomé Valls, et al. (2019) developed the ‘CMT – Circular Measurement Toolkit’, a tool to assess the degree of Circular Economy implementation in manufacturing small and medium enterprises. The toolkit is based on a questionnaire of 36 circularity factors grouped into eight sections, which range from

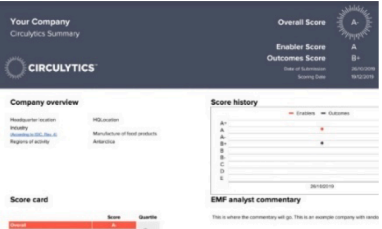

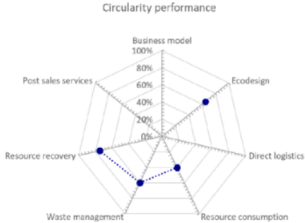

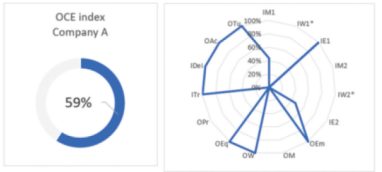
internal practices to internal and external awareness. The questionnaire adopts a three-level scale (yes; partially; no) for each item assessed. The result is an overall score (0–8 points) and a classification of the assessed SME in one of the eight available clusters. Gusmerotti et al. (2019) developed the ‘Circol-UP’ tool to measure the circularity performance of companies. The tool is shaped as a checklist of 15 qualitative evaluation items that assess the firm circularity across its supply chain (procurement, design, production, distribution, consumption, and waste management). The result is an aggregated circularity score for the firm (on a scale ranging from 0% to 100%). Based on the score, companies can be ranked as beginners, concerned, proactivist, or circular. The Ellen MacArthur Foundation (2020) developed ‘Circulytics’, a tool to assess the Circular Economy performance of a company operations. It is based on a set of 38 indicators structured into enablers (i.e., critical aspects to enable a company-wide transformation such as strategy and planning, innovation, people and skills, operations, and external engagement) and outcomes (i.e., metrics that assess how circular a company is, focusing on their products, materials, services, assets, water, energy, and finance). Based on the answers provided, Circulytics delivers an overall alphabetical score (from A to E) as a result of a weighted average between enablers and outcomes. Pigosso & McAloone (2021) developed the ‘MATChE’ tool to measure the readiness of manufacturing organizations for implementing circularity. The assessment is based on 30 questions grouped into 8 areas, which range from company strategy and organization to product and business model innovation. Each item is evaluated on a five-level scale that assesses the degree of implementation into the company (from not started to a full-scale implementation). The tool then provides an overall readiness score on a 0–150 points scale. The tool allows benchmarking and provides recommendations on how to better kickstart the company journey towards Circular Economy. Sacco et al. (2021) developed the ‘CM-FLAT’ tool to evaluate both the maturity (i.e., the presence of documented Circular Economy activities) and circularity (i.e., the obtained Circular Economy results). The tool is based on a questionnaire that contains 43 pre-defined multiple-choice questions, grouped into seven specific areas. The result is an overall score (0–100%) that provides the levels of maturity and circularity. Urain et al. (2022) developed the ‘ICEQ – Industrial Circular Economy Questionnaire’, a self-diagnostic tool aimed at helping Basque industrial companies in assessing their internal and external contexts in relation with the Circular Economy. The questionnaire is based on 165 questions related to ten different areas divided into internal (strategic, operational, and supporting processes) and external (market, society, technology, customers, stakeholders) contexts. The result is an overall score, ranging from 0 to 5 points, which provides the level of circularity of the assessed organization. The score is the starting point for the definition of an action plan to address Circular Economy opportunities. Lastly, Baumer-Cardoso et al. (2023) developed the ‘OCE – Overall Circularity Effectiveness’ tool to assist companies in quantitatively assessing their level of adoption of Circular Economy. The tool is based on 15 quantitative indicators that compute the inputs and the outputs of a production system, thus focusing on the assessment of the level of reduction of the use of natural resources, emissions, materials losses, including the share of renewable and recyclable resources, the promotion of employee wellbeing and, lastly, the degree to which products, components, materials, and assets retain their value in the economy. The result is an

Table 2
Overview of tools to measure the level of readiness of manufacturing companies for the Circular Economy.

Name of the tool	Objective	Scope	Areas of analysis	Items	Results	Visualization of results	Key Circular Economy implementation areas											
							Product structure	Production process	Business model	Supply Chain	Regeneration	Green culture and habits						
Circular Economy Toolkit (Evans & Bocken, 2014)	To assess products and services circularity level and their potential enhancement	Product	7 areas: Design, manufacture, and distribution; Usage; Maintain and repair; Reuse/redistribution of the product; Refurbishment and remanufacturing of product parts; Products as a service; Recycling at end of life	33	Circularity improvement potential score (low-medium-high) for each area and a list of suggestions on how to improve the targeted areas.	<p>Improvement Potential ■ High ■ Medium ■ Low</p>	✓	✓	✓		✓							
CEIP – Circular Economy Indicators Prototype (Cayzer et al., 2017)	To measure and evaluate the circularity performance of products	Product	5 areas: Design; Production; Commercialisation; Utilisation; End of Life	15	Overall circularity aggregated score (0–100%) and spider chart for each area	<p>RESULTS OUTPUT</p> <table border="1"> <tr> <th>Product Rating</th> <th>Product Ranking</th> <th>Points</th> </tr> <tr> <td>63%</td> <td>Good</td> <td>Scored: 96 Available: 152</td> </tr> </table>	Product Rating	Product Ranking	Points	63%	Good	Scored: 96 Available: 152	✓	✓	✓		✓	
Product Rating	Product Ranking	Points																
63%	Good	Scored: 96 Available: 152																
CMT – Circularity Measurement Toolkit (Garza-Reyes, Salomé Valls, et al., 2019)	To measure the degree of circularity for small and medium enterprises	Company	8 areas: Internal practices (design and production); Internal awareness and external awareness; Value chain; Longevity of materials, components, and products; Green market; R&D; Legislation	36	Overall circularity score (0–8 points) and identification of an enterprise category based on the overall score obtained		✓	✓	✓	✓	✓	✓						
Circol-UP (Gusmerotti et al., 2019)	To measure the firm circularity performance, overall and for each product lifecycle stage	Company	6 areas: Procurement; Design; Production; Distribution; Consumption; Waste prevention and management	15	Corporate circularity score (0–100%) and benchmarking	<p>Circ Index: 26%</p>	✓	✓	✓	✓	✓							

(continued on next page)

Table 2 (continued)

Name of the tool	Objective	Scope	Areas of analysis	Items	Results	Visualization of results	Key Circular Economy implementation areas					
							Product structure	Production process	Business model	Supply Chain	Regeneration	Green culture and habits
Circulytics (Ellen MacArthur Foundation, 2020)	To capture the circular economy performance of a company operations	Company	2 areas: Enablers (Strategy and Planning; Innovation; People and Skills; Operations and External Engagement); and Outcomes (Products and Materials; Services; Pant, Property and Equipment Assets; Water; Energy and Finance).	38	Overall circularity score (from A to E) based on a weighted average between enablers and outcomes.		✓	✓	✓	✓	✓	✓
MATChE (Pigosso & McAloone, 2021)	To measure the readiness of manufacturing organizations for implementing circularity	Company	8 areas: Organization; Strategy & Business Model; Product & Service Innovation; Manufacturing & Value Chain; Technology & Data; Use, Support & Maintenance; Takeback & End-of-life; Policy & Marke	30	Circularity readiness score (0–150 score), benchmarking and tailored recommendations on how to kickstart the Circular Economy transition.		✓	✓	✓	✓	✓	✓
CM-FLAT – Circularity and Maturity Firm-Level Assessment (Sacco et al., 2021)	To measure company level of Circular Economy maturity and circularity	Company	7 areas: Product structure; Production process; Business model; Use and maintenance; Supply chain; Regeneration; End of life	43	Overall circularity score (0–100%), and specific radar charts (per area) of the level of maturity and circularity attested		✓	✓	✓	✓	✓	✓
ICEQ – Industrial Circular economy Questionnaire (Urain et al., 2022)	To measure the level of company circularity	Company	10 areas: Strategic processes; Operational processes and Support processes; Society; Environmental; Market; Legislative; Technological; Clients, and Stakeholders.	165	Overall (0–5 points) circularity score and definition of company class (incipient, basic, operational, commitment, strategic)		✓	✓	✓	✓	✓	✓
OCE – Overall Circularity Effectiveness (Baumer-Cardoso et al., 2023)	To assist companies in quantitatively showcasing their level of Circular Economy adoption	Company	15 areas (indicators): Use of natural resources; emissions; material and water losses; share of renewable and recyclable resources; promotion of employee wellbeing; products, components, materials, and assets value retention.	15	Overall circularity score (0–100%) based on the aggregation of 15 quantitative indicators		✓	✓	✓	✓	✓	✓

overall index that ranges from 0 to 100% and assesses how much Circular Economy characteristics are fulfilled at the company level.

The evaluation elements employed by each tool have been then categorized according to the key Circular Economy implementation areas of product design, production process, business model, supply chain, regeneration, and green culture and habits (Fig. 2).

The distribution of the evaluation elements across the six areas reported in Fig. 2 reveals that the earliest tools designed to assess companies readiness for a Circular Economy focused primarily on the product structure area, with secondary emphasis on business model redesign and the regeneration of end-of-life products via reuse, remanufacturing, and recycling (Cayzer et al., 2017; Evans & Bocken, 2014). Over time, however, tools began to cover additional aspects outside the traditional boundaries of the organization being assessed. At the supply chain level, tools began to incorporate elements such as the presence of circularity criteria in suppliers selection, the optimization of transportation routes, or collaboration with suppliers and customers for the design of circular solutions (Ellen MacArthur Foundation, 2020; Sacco et al., 2021; Urain et al., 2022). Tools also introduced aspects related to company green culture and habits, aiming to support the integration of Circular Economy principles throughout the whole organization (Pigosso & McAlloone, 2021). These elements include the establishment of a circular strategy and action plan, as well as the presence of a structured sustainability reporting for circularity performances (Urain et al., 2022). The analysis also shows the presence of two distinct groups of tools. The first group comprises vertical tools where a large share of evaluation items (40–50%) focuses on a single key Circular Economy area such as product structure (Cayzer et al., 2017; Evans & Bocken, 2014), production processes (Baumer-Cardoso et al., 2023) or green culture (Ellen MacArthur Foundation, 2020). In contrast, the second group of tools adopts a more horizontal and comprehensive perspective that follows a balanced approach of the evaluation elements across the different dimensions, covering the six key Circular Economy implementation areas more evenly (Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Pigosso & McAlloone, 2021; Sacco et al., 2021; Urain et al., 2022).

Nevertheless, tools show a variety of approaches and a general disagreement on which specific evaluation elements and circularity criteria should be used for assessing the readiness of manufacturing organizations for the Circular Economy (Camacho-Otero & Ordoñez, 2017; de Oliveira & Oliveira, 2023; Jerome et al., 2022; Moraga et al.,

2019; Vinante et al., 2021). Some tools neglect supply chain aspects (Baumer-Cardoso et al., 2023; Evans & Bocken, 2014) or circularity opportunities in general company culture and green habits (Cayzer et al., 2017; Gusmerotti et al., 2019). Even for tools covering all the six key Circular Economy areas, the number and type of evaluation elements adopted largely differ. As a result, the complexity of the Circular Economy paradigm is still far from being fully considered by existing tools (Chrispim et al., 2023; Helander et al., 2019; Saidani et al., 2017).

Most importantly, current tools overlook the crucial aspect of decarbonization of manufacturing companies when designing strategic Circular Economy implementation roadmaps. Some tools include, in addition to the assessment of the Circular Economy readiness, indications on how to better kickstart this transition to increase circularity (Evans & Bocken, 2014; Pigosso & McAlloone, 2021). However, all the suggested actions are limited to improving the company level of circularity. For prioritizing Circular Economy actions for decarbonization purposes, companies with limited resources need simple yet effective tools able to combine their Circular Economy readiness with carbon footprint evaluations. The available tools in literature overlook this aspect, thus failing to provide adequate guidance on the prioritization of Circular Economy strategies to reduce carbon emissions.

4.2. The C-Readiness tool

C-Readiness is a tool specifically designed for assessing the readiness of manufacturing companies for the Circular Economy and for prioritizing Circular Economy actions for undertaking a decarbonization path. While maturity models assess the current level of maturity of an organization for a defined topic, readiness tools determine the organization preparedness to embark on a new development process (Acerbi et al., 2024; Chari et al., 2023; Chirumalla et al., 2024; Hernandez de Paula e Silva, Coser Mergulhão, Geraldo Vidal Vieira, Brasco Pampanelli, & Salvador, 2024; Kayikci et al., 2022; Kurilova-Palisaitiene et al., 2024; Uhrenholt et al., 2022; Zomer et al., 2024). The tool consists of 33 evaluation elements, grouped into six areas that are key for the implementation of Circular Economy in manufacturing organizations. The selected evaluation elements are listed in Table 3.

The first area ('Product structure') aims at measuring the level of circularity at the product design level. The evaluation elements cover the strategies for circular product redesign in terms of materials used and Bill of Materials structure. They include elements such as the use of

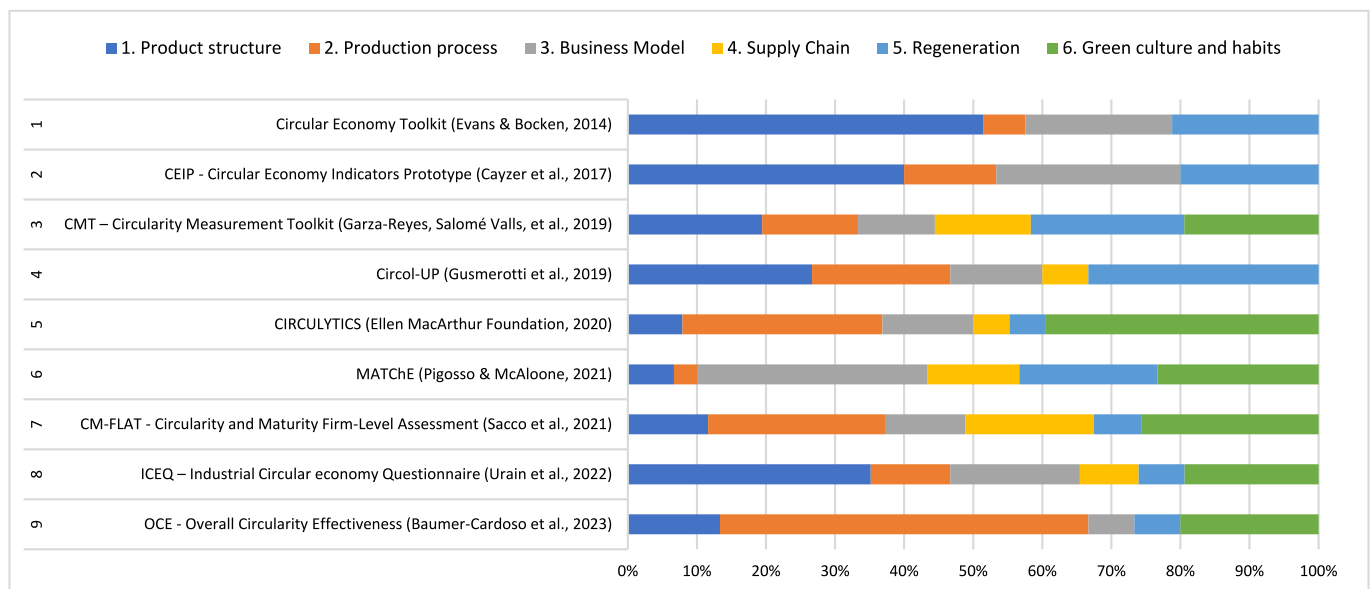


Fig. 2. Critical comparison of previous tools: share of evaluation elements for each key Circular Economy area.

Table 3

C-Readiness key areas and evaluation elements.

Area	ID	C-Readiness evaluation element	References
1. Product structure	1.1	To what extent the materials used in your products are biodegradable, recyclable, and/or recycled?	(Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Urain et al., 2022)
	1.2	Do your products contain toxic materials (e.g., subject to REACH directive or disposal restrictions)?	(Evans & Bocken, 2014)
	1.3	Do your products contain materials that are critical in terms of availability and supply?	(Evans & Bocken, 2014; Urain et al., 2022)
	1.4	Do your products have any environmental product certifications (e.g., EPD, Cradle-2-Cradle, etc.)?	(Garza-Reyes, Salomé Valls, et al., 2019; Urain et al., 2022)
	1.5	To what extent the products and their components are designed for the Circular Economy (durability, modularity, standardization)?	(Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022)
2. Production process	2.1	How much scraps and production waste account on the total volume produced?	(Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Sacco et al., 2021; Urain et al., 2022)
	2.2	Is there a monitoring system for tracking the consumption of resources (energy, water, etc.) during manufacturing?	(Ellen MacArthur Foundation, 2020; Urain et al., 2022)
	2.3	To what extent the energy consumed for manufacturing is generated from renewable sources?	(Baumer-Cardoso et al., 2023; Ellen MacArthur Foundation, 2020; Garza-Reyes, Salomé Valls, et al., 2019; Sacco et al., 2021; Urain et al., 2022)
	2.4	To what extent are industrial symbiosis mechanisms applied (if any) in your manufacturing plants?	(Pigosso & McAloone, 2021; Sacco et al., 2021)
	2.5	Is there an environmental management system (e.g., ISO 14001) in your manufacturing plants and, if so, to what extent is it applied?	(Urain et al., 2022)
3. Business Model	3.1	Does your company offer second-hand or regenerated products and, if so, to what extent this offering is spread?	(Evans & Bocken, 2014; Pigosso & McAloone, 2021; Urain et al., 2022)
	3.2	Does your company offer product-service systems solutions such as product leasing, renting, pay-per-use and, if so, to what extent these offerings are spread?	(Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022)
	3.3	To what extent is it possible to share your products	(Pigosso & McAloone, 2021; Urain et al., 2022)

Table 3 (continued)

Area	ID	C-Readiness evaluation element	References
4. Supply Chain	3.4	among different users (product sharing)? To what extent does your company use cloud-based trading platforms for scraps and waste?	(Pigosso & McAloone, 2021)
	3.5	To what extent does your company collaborate with value chain partners to co-design product-service systems for the Circular Economy?	(Ellen MacArthur Foundation, 2020; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022)
	4.1	To what extent your company can track products, components, and materials along the supply chain (e.g., through sensors, IoT, RFID, blockchain technologies)?	(Pigosso & McAloone, 2021)
	4.2	To what extent does your company select suppliers based on green criteria and on their environmental performances?	(Ellen MacArthur Foundation, 2020; Garza-Reyes, Salomé Valls, et al., 2019; Sacco et al., 2021; Urain et al., 2022)
	4.3	To what extent is the packaging of your products made from sustainable (e.g., recycled) materials?	(Cayzer et al., 2017; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Urain et al., 2022)
5. Regeneration	4.4	To what extent does your company apply systematic methods to optimize distribution networks to minimize their environmental impact by reducing transportation needs?	(Gusmerotti et al., 2019; Sacco et al., 2021)
	4.5	To what extent does your company use sustainable mode of transportation?	(Sacco et al., 2021)
	5.1	Are there any products take-back initiatives directly organized by the company and, if so, to what extent these initiatives are diffused?	(Ellen MacArthur Foundation, 2020; Pigosso & McAloone, 2021; Sacco et al., 2021)
	5.2	Is there a reverse logistics system for your end-of-life products and, if so, to what extent your company manage and control its infrastructures?	(Gusmerotti et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022)
	5.3	To what extent do initiatives for the reuse of your products exist and are widespread?	(Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022)
5.4	5.4	To what extent do initiatives for the remanufacturing of your components exist and are widespread?	(Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Urain et al., 2022)
	5.5	To what extent do initiatives for the recycling of your materials exist and are widespread?	(Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Pigosso &

(continued on next page)

Table 3 (continued)

Area	ID	C-Readiness evaluation element	References
6. Green culture and habits	5.6	To what extent do your products end up in landfill when they reach the end of their life?	McAloone, 2021; Sacco et al., 2021; Urain et al., 2022) (Ellen MacArthur Foundation, 2020; Urain et al., 2022)
	6.1	To what extent does your company have implemented actions aimed at eliminating single-use plastics within the organization?	(Foschi et al., 2021; Urain et al., 2022)
	6.2	To what extent has your company eradicated single-use plastic from drinking water consumption in the organization?	(Foschi et al., 2021; Urain et al., 2022)
	6.3	To what extent has your company eradicated single-use plastic from coffee consumption in the organization?	(Foschi et al., 2021; Urain et al., 2022)
	6.4	To what extent has your company eradicated single-use plastic from the canteen areas of the organization?	(Foschi et al., 2021; Urain et al., 2022)
	6.5	To what extent are waste sorting and separate collection for recycling applied inside the organization?	(Ellen MacArthur Foundation, 2020; Garza-Reyes, Salomé Valls, et al., 2019)
	6.6	Are there any sustainable mobility initiatives for employees and, if so, to what extent these initiatives are diffused?	(Baumer-Cardoso et al., 2023)
	6.7	To what extent does your company communicate its environmental performances externally?	(Pigosso & McAloone, 2021; Sacco et al., 2021)

biodegradable, recyclable or recycled materials; the non-use of toxic materials in the design of products; the non-use of critical raw materials; and the extent to which products are designed for circularity through material durability, standardization, and modularity (Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Urain et al., 2022). Companies investing in these circular product redesign actions minimize the need for the extraction of virgin resources. By reducing the demand for virgin material extraction processes, the carbon emissions generated at the material extraction stage are reduced (Gallego-Schmid et al., 2020; Gallo et al., 2023).

The second area ('Production process') aims to evaluate the circularity of a company in its manufacturing activities. The selected evaluation elements include, for instance, the incidence of scraps and production waste in relation to the total volumes produced; the share of energy produced from renewable sources such as photovoltaic panels; or the adoption of industrial symbiosis mechanisms for trading resources in excess (Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Sacco et al., 2021; Urain et al., 2022). Companies investing in these circular production activities enhance resource efficiency and increase the share of energy consumption that is not produced through the combustion of fossil fuels. As a consequence, they reduce the carbon emissions generated at the production stage (Brändström & Saidani, 2022; Gallo et al., 2023).

The third area ('Business Model') aims to assess how the company creates circular value through the offering of its products and services. The way in which products are offered to customers strongly affects the

circularity of the company, especially if product-as-a-service business models are employed (Bressanelli et al., 2024). Selected evaluation elements include the presence and diffusion of product-service systems solutions such as product leasing, renting and pay-per-use, or the possibility to share the product among multiple users (Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022). Companies investing in new business models such as leasing and sharing promote resource efficiency during the use of their products, since products are frequently maintained and upgraded for optimal energy efficiency (Pialot et al., 2017). These circular business models thus contribute in lowering carbon emissions at the usage stage (Bressanelli et al., 2024).

The fourth area ('Supply Chain') aims to measure the circularity of a company in procurement and distribution activities. Evaluation elements include, for instance, the selection of suppliers based on green criteria and their environmental performances, the optimization of the distribution network to minimize environmental impacts, or the use of environmental-friendly transport carriers (Ellen MacArthur Foundation, 2020; Garza-Reyes, Salomé Valls, et al., 2019; Sacco et al., 2021; Urain et al., 2022). Companies investing in circular supply chain management optimize their inbound and outbound logistics activities, minimizing the number of trips, selecting energy-efficient transportation modes, and prioritizing local suppliers over global ones. Therefore, companies investing in this area reduce carbon emissions at the transportation and distribution stage (Dubisz & Golinska-Dawson, 2021; Gallo et al., 2023).

The fifth area ('Regeneration') aims to evaluate the circularity of a company when its products reach the end-of-life. Evaluation elements include, for instance, the existence and diffusion of products take-back initiatives organized by the company; and the existence and diffusion of initiatives for the reuse, remanufacturing, and recycling of products, components and materials (Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Garza-Reyes, Salomé Valls, et al., 2019; Gusmerotti et al., 2019; Pigosso & McAloone, 2021; Sacco et al., 2021; Urain et al., 2022). Companies that invest in regeneration processes minimize the waste sent to landfills and reduce the need for new, virgin materials. These results allow reducing the carbon emissions at the end-of-life stage, since reuse and recycling reduce the methane emissions associated with waste decomposition in landfills, and lead to avoided impacts in the carbon emissions associated with the production of new materials, which are usually accounted as 'carbon credits' at the end of life (Boldoczki et al., 2020; Yuan et al., 2016).

The sixth and last area ('Green culture and habits') aims at assessing the circularity of a company based on the evaluation of general cross-company good practices, analyzing various environmentally sustainable behaviors with a focus on the adoption of plastic-free strategies by companies (Foschi et al., 2021). Evaluation elements include, for instance, the existence and diffusion of actions aimed at eliminating single-use plastics within the organization; the existence and diffusion of sustainable mobility initiatives for employees; the external communication of the company environmental performance (Pigosso & McAloone, 2021; Sacco et al., 2021).

A five-level scale was then designed to assess each evaluation element. Options range from 'Not at all' (0 points) to 'Few applied' (25 points), 'Somewhat applied' (50 points), 'Very applied' (75 points), and 'Fully applied' (100 points). If the option 'Not applicable' is chosen, the evaluation element is excluded from the computation of the C-Readiness score. Consequently, the C-Readiness score of each j -th area can be computed by considering the points P_i assigned to each i -th evaluating element, as of Eq. (1). By doing so, each area (from product structure to green culture and habits) receives a score (ranging from 0 to 100 points), which describes its readiness for the Circular Economy. If more respondents from the same company are involved in the evaluation, the statistical 'mode' (i.e., the value that appears most frequently) is used to aggregate answers and obtain a unique score for the company. The use

of the mode is particularly useful when dealing with categorical data (G. James et al., 2021). Results are then plotted into a spider-diagram to increase their understandability through visualization.

$$C_{R_{i-\text{Area}}} [0 - 100\text{points}] = \frac{\sum_i P_i}{|i|} \quad (1)$$

Then, the company comprehensive C-Readiness score is computed as the average of the individual scores of each area. To prioritize Circular Economy actions for decarbonization purposes, the scores previously computed are combined with the carbon footprint of the representative product of the organization under investigation. A product LCA analysis should then be carried out, and the carbon footprint results should be segmented for each life cycle stage (raw materials extraction, production processes, transportation and distribution, usage, and end of life). Product carbon footprint results can be provided by companies (if available) or estimated by the managers involved in the C-Readiness evaluation, based on available information. These results are used for creating a percentage distribution of the total product carbon footprint across lifecycle phases. For instance, in the case of a washing machine, the carbon footprint of the product over the life cycle stages can be distributed as follows (Boyano et al., 2017; Otterbach & Fröhling, 2024; Yuan et al., 2016): material extraction 15%; production and assembly 10%; distribution and transportation 5%; use of the product 65%; end of life 5%. The C-Readiness tool then assigns each key Circular Economy area to the specific representative product life cycle stage that would benefit the most from potential Circular Economy investments. As explained above, circular investments in the 'Product structure' area would potentially affect and reduce mainly the environmental impact related to raw materials extraction. Investments in the 'Production process' area would potentially affect and reduce mainly the environmental impact related to production processes. Investments in the 'Business Model' area would potentially affect and reduce mainly the environmental impact related to products usage. Investments in the 'Supply Chain' area would potentially affect and reduce mainly the environmental impact related to transportation and distribution. Investments in the 'Regeneration' area would potentially affect and reduce mainly the environmental impact related to products end of life. The area 'Green culture and habits', instead, has not been assigned to any life cycle stage, given their general characteristics and the fact that they do not have a direct impact on any specific life cycle stage.

This cross-analysis provides interesting indications on which Circular Economy areas should be prioritized for investments by companies for decarbonization (Fig. 3). Companies should prioritize investments in Circular Economy areas with a high carbon footprint but with low C-

Readiness score (*Investment*), while areas with low carbon footprint and low C-Readiness score can be neglected (*Irrelevance*). Circular Economy areas with a high C-Readiness score but low carbon footprint are good candidates for being exploited for external communication and reporting (*Green marketing*). Lastly, Circular Economy areas with a high carbon footprint and with a high C-Readiness score represent core domains in which the company has already invested in circularity in the past (*Circular core*). Thus, they can be leveraged for further progress in other areas.

4.3. Case studies

4.3.1. Alpha

Alpha is a global leader in the production of valves and systems tailored for the treatment, distribution, control, and metering of various fuels and gases across diverse supply chains. Originating as a family enterprise in the 1950s, the company has grown through strategic international partnerships, joint ventures, and acquisitions to broaden its product portfolio. Currently, Alpha product range includes valves and accessories for gas distribution in the energy sector, for refrigerant services, and for high pressures industrial applications. As of 2023, Alpha turnover approached € 165 million worldwide, with a workforce of approximately 400 people spread across 15 sites encompassing manufacturing facilities and subsidiary distributors. The C-Readiness assessment was carried out by Alpha quality manager.

Overall, the company obtained a C-Readiness score of 33 points out of 100 (Fig. 4). Alpha obtained the highest score in company green culture and habits (68 points), due to widespread initiatives that involve the implementation of internal environmental policies coupled with employers' active involvement in plastic reduction, waste minimization and sorting across various regions. Moreover, a high score was obtained in production processes (55 points), due to the existence of structured waste and resources tracking and environmental management systems, the prioritization of renewable and sustainable energy sources (including photovoltaic), and the minimization of production scraps. On the other hand, lower scores were obtained in the product structure and supply chain areas. In the former, Alpha obtained a score of 45 points, due to the moderate use of recyclable materials during products design, the commitment to eliminating toxic materials and the almost absence of critical raw materials at the procurement stage. Nevertheless, further improvements can be achieved through the implementation of circular product design strategies such as standardization and modularization. In the latter, instead, Alpha obtained a score of 30 points, due to the lack of both a structured suppliers' selection according to environmental

		C-Readiness score	
		Low	High
Carbon Footprint relevance	High	<p>Investment quadrant (High carbon footprint but low C-Readiness score)</p> <p>Companies should prioritize investments in these key Circular Economy areas for decarbonization purposes</p>	<p>Circular core quadrant (High carbon footprint and high C-Readiness score)</p> <p>Companies can leverage on these key Circular Economy areas for implementing other actions</p>
	Low	<p>Irrelevance quadrant (Low carbon footprint and low C-Readiness score)</p> <p>These key Circular Economy areas can be neglected for investments for decarbonization purposes</p>	<p>Green marketing quadrant (Low carbon footprint but high C-Readiness score)</p> <p>Companies can exploit these key Circular Economy areas for external communication and reporting</p>

Fig. 3. Prioritization matrix with the four quadrants Investment, Circular core, Irrelevance, and Green marketing.

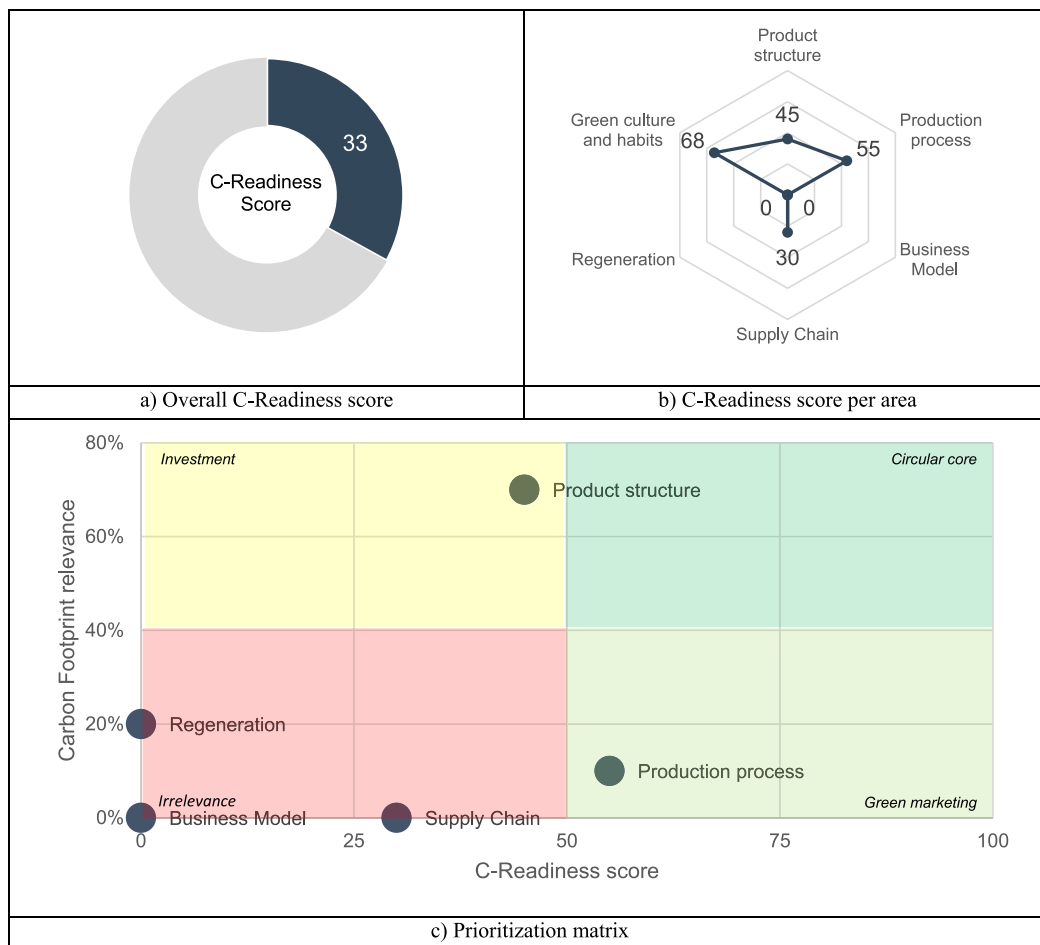


Fig. 4. C-Readiness results for Alpha.

aspects and products tracking mechanisms along the supply chain. Lastly, both business model and end of life management areas scored 0 points, representing untapped potential in alternative business models and unexploited reuse, remanufacturing, and recycling techniques.

The C-Readiness score was then combined with the quantitative evaluation of the carbon footprint of the representative product of the company. The carbon footprint profile was supplied by the company. Accordingly, raw materials accounted for nearly the 70% of the total carbon footprint, followed by end of life (20%) and production processes (10%). Despite circular business models and products regeneration at end of life may be strategic for some company decarbonization paths, their contribution to the reduction of Alpha carbon footprint is negligible, due to the limited impact on climate change of products usage and end of life phases. Therefore, Alpha should give low priority to the implementation of Circular Economy actions on these two areas. On the other hand, product design scored as an area with a high (relative) environmental impact and for which the company has not achieved yet an acceptable circularity score. Therefore, the company should prioritize investments on the implementation of circular product redesign strategies such as extending the useful life of Alpha valves by employing more durable materials – thus making them wear-resistant and counteracting their obsolescence – as well as increasing their modularity and standardization to reduce the number of components and facilitate the inspection of products during maintenance and repair. Lastly, the circularity efforts already taken in the production process areas can be used by the company for green marketing purposes, since the environmental impact of production processes (compared to others life cycle stage) is negligible. Communicating them externally can help in engaging stakeholders and increasing the company public green image.

4.3.2. Beta

Beta is a small-sized enterprise specialized in the production of intricate embroidery and decorations for textile products and applications. As of 2023, the company turnover approached € 2 million, employing 20 employees in its facility located in the North-Centre of Italy. Here, Beta exploited its excellence in craftsmanship, blending artisanal mastery with creativity and cutting-edge technologies to provide tailored embroidery and solutions for luxury fashion brands. The C-Readiness assessment for Beta involved four people: the company CEO, the purchasing manager, the production manager, and the finance and control administration manager.

Overall, the company obtained a C-Readiness score of 29 points out of 100 (Fig. 5). Although this (low) overall score, Beta obtained high results in the areas of product design (57 points) and company green culture and habits (51 points), due to the company efforts in the design of circular embroidery to minimize waste, the pursuit of environmental product certifications, and the actions already undertaken to reduce single-use plastics in offices and laboratories and to raise awareness among internal employees and external stakeholders of the sustainability concerns of the textile industry. However, Beta obtained lower scores in the other areas. For the Supply Chain, Beta puts efforts in the engagement of the whole supply chain to obtain the Global Organic Textile Standard certification, but shortcomings in material tracking systems, in suppliers' selection and evaluation, and in logistics optimization were detected (27 points). For production processes, Beta obtained a score of 17 points, due to the high impact of scrap and waste generated during the embroidery realization process, and the absence of a formalized system to track and manage them. Lastly, untapped opportunities were found in Business Model (14 points) and end of life (9

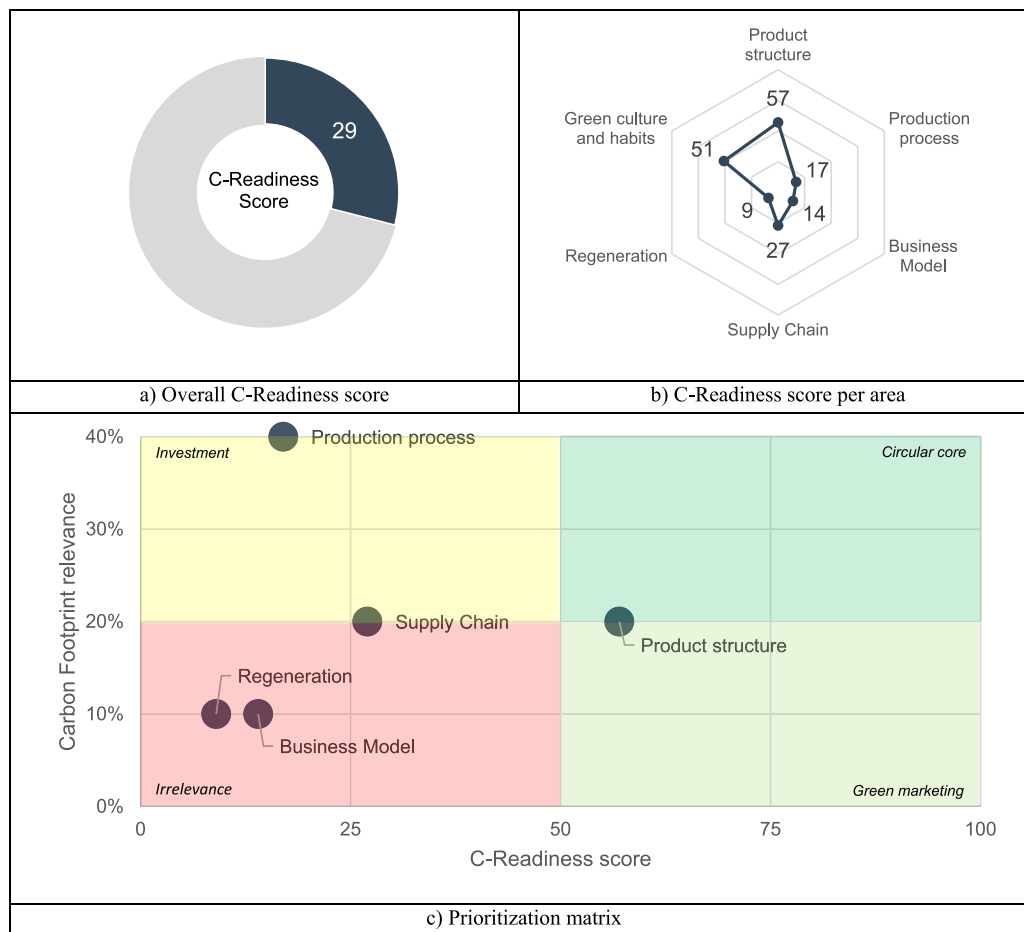


Fig. 5. C-Readiness results for Beta.

points) areas, due to difficulties in implementing product-service systems solutions and the fact that Beta, being a subcontractor of fashion brands, does not directly manage the sale and disposal of the textile product on which the embroidery is made.

The C-Readiness score was then combined with the quantitative evaluation of the carbon footprint of the representative product of Beta. The carbon footprint profile was estimated by the company managers. Accordingly, production processes accounted for 40% of the total carbon footprint. Raw materials and distribution impacted 20% each, while the usage and the end-of-life phases impacted 10% each. Despite their low circular readiness, investments in regeneration and business models can be avoided because of their low (relative) environmental impact. To achieve more consistent decarbonization targets, the tool suggests focussing on other potential Circular Economy areas of action. The key investment area for Beta is the production process: the low C-Readiness score suggests room for improvement, and the high (relative) carbon footprint establishes its prioritization for decarbonization. Therefore, Beta should implement industrial symbiosis actions to foster the recovering and reuse of its production offcuts and scraps. This, in turn, will boost Beta circularity and potentially lead to significant decarbonization results.

4.3.3. Gamma

Gamma is a leading company in the manufacturing of professional coffee machines. Founded in the 1930s, the company owes its success to its ability in crafting its own line of premium machines, contributing to the worldwide spread of the espresso culture. Over the past two decades, Gamma has grown from being a family-owned company to a multinational corporation with subsidiaries all over the world. As of 2023, its

turnover hit 135 million € with a workforce of 300 employees. Gamma underwent the C-Readiness assessment, which involved four people: the company Chief Operating Officer, the quality manager, the sales manager, and the R&D manager.

The company obtained an overall C-Readiness score of 58 points out of 100 (Fig. 6), showcasing excellent scores in company green culture and habits (92 points), in product design (74 points), in Supply Chain (74 points), and in production processes (61 points). Key endeavors include the adoption of circular design practices such as standardization and modularization to favor maintenance and product life extension, the continuous monitoring of production processes as well as the limited incidence of scraps and production waste, the generation of energy from photovoltaic panels installed on the Italian facilities that, on average, generated approximately the 50% of the energy needed for production, the tracking of materials along the supply chain, the optimization of product distribution and the selection of suppliers according to sustainability criteria, as well as the Gamma steadfast dedication and engagement in social endeavours such as coffee plantation preservation and fostering awareness about its cultivation. Despite that, both Business Model (17 points) and End of Life (32 points) areas obtained below-average scores.

The C-Readiness score was then combined with the quantitative evaluation of the carbon footprint of the representative product of Gamma. The carbon footprint profile was supplied by the company. Accordingly, raw materials accounted for 30% of the total carbon footprint, production processes for 10%, distribution for 20%, the usage phase for 25%, and the end-of-life for 15%. In this case, based on the C-Readiness tool application, the company should prioritize strategic investments in new business models based on the leasing of high-quality,

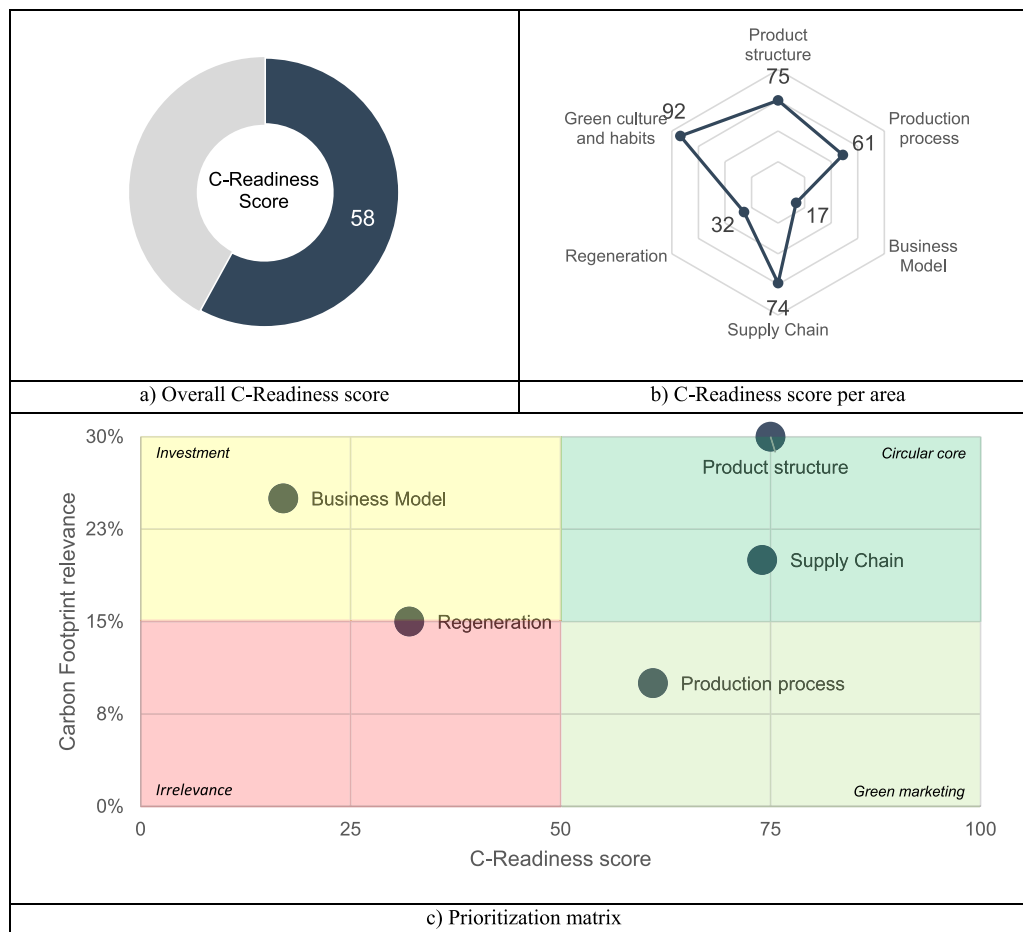


Fig. 6. C-Readiness results for Gamma.

high-efficient coffee machines. Thanks to the adoption of leasing business models, customers do not have to immediately pay the (high) price of Gamma high-quality coffee machines, thus encouraging the large-scale diffusion of highly energy efficient models. This will contribute to lowering carbon emissions connected with the usage phase such as energy and water consumption. The digitalization of Gamma coffee machines through Internet of Things will play a pivotal role in enabling these business models, facilitating the access to sustainable options for coffee consumption. The adoption of these circular business model will be facilitated by the actions already done by Gamma in product modular design, production processes, and supply chain areas, and will highly contribute to the Gamma decarbonization strategy.

4.3.4. Delta

Delta is an Italian company specialized in the manufacturing of highly adaptable pallet wrapping and handling systems. Established in the 1970 s, the company main business unit is the crafting of end-of-line packaging solutions tailored to the unique requirements of customers. As of 2023, Delta reached a turnover of about € 11 million, with 45 employees. Delta competitive advantage relies on its fully automated systems and comprehensive turnkey solutions and services to support customers in implementing, integrating, and maintaining pallet wrappers effectively. The C-Readiness assessment involved three people from Delta: the CEO, the innovation manager, and the sales director.

Overall, the company obtained a C-Readiness score of 32 points out of 100 (Fig. 7). In terms of product design (40 points), Delta demonstrated a commitment to circularity by prioritizing recyclable materials and designing machinery for longevity. While there are still some components containing toxic materials, the company plans to phase

them out in the short term. Delta production processes obtained 41 points, particularly for the low waste impact and moderate use of renewable energy sources. Implementing a production monitoring system could further optimize materials and energy use during manufacturing. General company green culture and habits obtained 44 points, due to the employed actions for reducing single-use plastic consumption in offices and facilities. Nevertheless, the other areas obtained scores well-below the average. Delta supply chain (27 points) currently lacks alignment with overall sustainability goals. The company recently started initiatives to actively engage stakeholders, but there are still untapped opportunities in the optimization of the distribution network and in the selection of suppliers based on environmental criteria. Regarding the business model (22 points), Delta is still focused on the sale of pallet wrappers and on offering traditional, product-oriented services such as maintenance and repair. Lastly, and although Delta recognizes the importance of reconsidering the end of life of its products, most materials and components still end up in landfills when pallet wrappers are disposed of (19 points).

The C-Readiness score was then combined with the quantitative evaluation of the carbon footprint of the representative product of Delta. The carbon footprint profile was estimated by the managers of the company. Accordingly, the end-of-life accounts for 30% of the total carbon footprint. Raw materials account for 30% too, followed by usage (25%), distribution (10%), and production processes (5%). To achieve decarbonization targets, product regeneration at the end of life represents a strategic opportunity for tapping into the potential of remanufacturing for the second-hand market. To capitalize on these opportunities, a heightened focus on the post-sale phase of pallet wrappers is imperative. According to C-Readiness results, Delta should

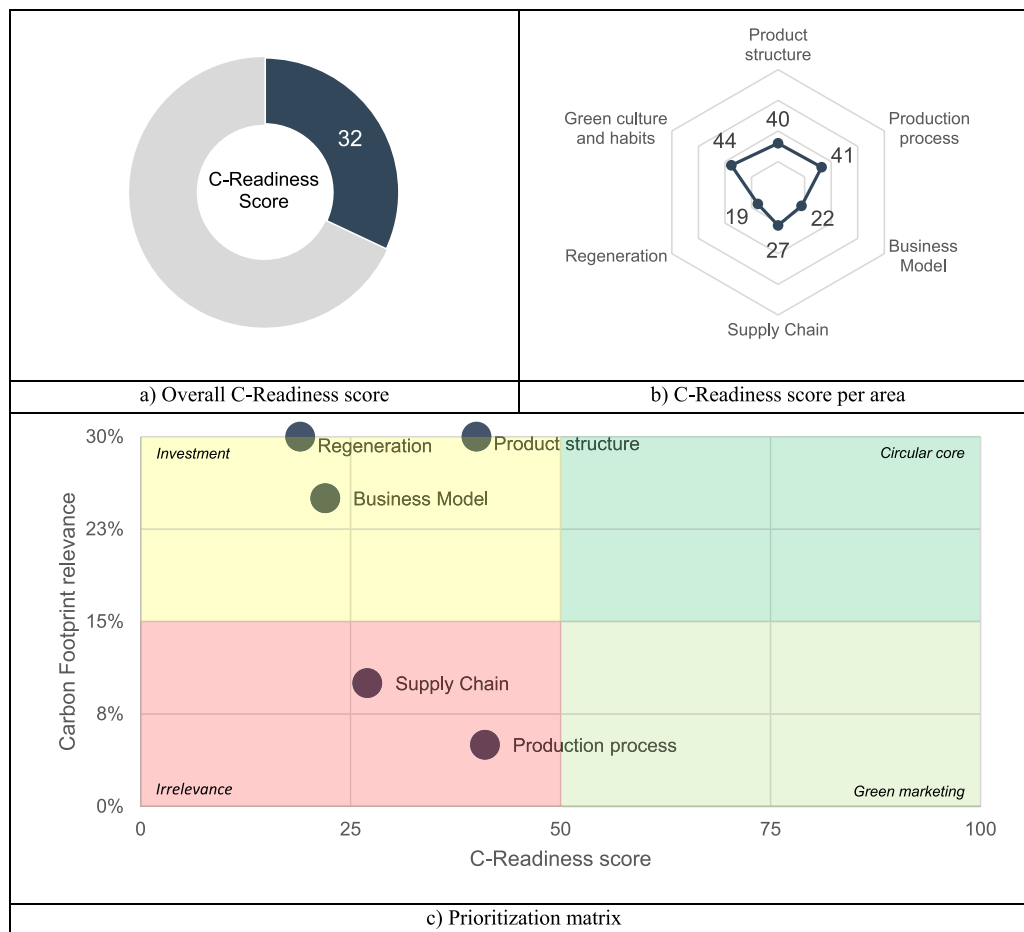


Fig. 7. C-Readiness results for Delta.

start the experimentation of initiatives to collect end-of-life pallet wrappers to recover their components and materials. This would minimize the volume of equipment that ends up in landfill and reduce the related carbon emissions. In addition, the C-Readiness results suggest shifting the focus of Delta from traditional to advanced service offerings in line with Circular Economy principles, such as the renting and leasing of pallet wrappers. In this way, products ownership remains with Delta, which is therefore incentivized to recover its products at the end of life. Lastly, redesigning pallet wrappers to adopt a modular structure will facilitate remanufacturing, as modular design makes disassembly easier.

5. Discussion

Although a systemic transition is needed, manufacturing companies need to prioritize Circular Economy actions to achieve decarbonization, given their resource constraints. To this aim, this paper develops and describes the C-Readiness tool, which has been structured around six key Circular Economy implementation areas. Compared to other tools, it takes a systemic and life cycle perspective, evaluating multiple Circular Economy implementation areas (Baumer-Cardoso et al., 2023; Cayzer et al., 2017; Ellen MacArthur Foundation, 2020; Evans & Bocken, 2014; Gusmerotti et al., 2019). The tool has also a general scope, and is not limited to the circularity evaluation of companies with specific characteristics such as small and medium-sized enterprises (Garza-Reyes, Salomé Valls, et al., 2019) or that are spatially confined in a defined geography (Urain et al., 2022). Most importantly, the C-Readiness tool advances the literature on Circular Economy since it couples the assessment of the circularity level of manufacturing organizations (Ellen MacArthur Foundation, 2020; Pigosso & McAlone, 2021), with

indications on which Circular Economy actions should be prioritized by a company to maximize the effects on decarbonization. This potential is practically shown thanks to the four case studies (Table 4). By graphically representing the results in a matrix, areas can be classified into four quadrants based on their Circular Economy readiness and carbon footprint results. Circular Economy actions in the 'Circular Core' quadrant are characterized by a high environmental impact, but the company is already prepared in terms of circularity. The 'Green marketing' quadrant includes Circular Economy actions where the company is already prepared for circularity, although the relative environmental impact is lower compared to other areas. Thus, companies can consider exploiting these Circular Economy areas for external marketing communication. Circular Economy actions in the 'Irrelevance' quadrant are those in which the company is not yet prepared for circularity but, due to the low environmental impact, the company can devote little attention to these areas in its decarbonization plan. Lastly, Circular Economy actions in the 'Investment' quadrant represent promising candidates for the company decarbonization strategy, as they display high relative environmental impact and a low Circular Economy readiness profile. Therefore, companies that invest in these actions can maximize decarbonization benefits with a focused investment effort. Through the C-Readiness tool, the four manufacturing companies obtained important insights on how Circular Economy actions can be exploited for reducing their carbon emissions. In fact, according to the C-Readiness scores, Alpha should invest in circular product design for durability and life extension, thus reducing carbon emissions connected with raw materials production and natural resources extraction. Beta should invest in industrial symbiosis mechanisms to enable the reuse of its textile production offcuts, thus reducing carbon emissions connected with production processes.

Table 4
Cross-case comparison and actions prioritized for decarbonization.

Company	Area	Irrelevance	Green Marketing	Circular Core	Investment	Circular Economy actions to prioritize for decarbonization
Alpha	Product structure				X	Alpha should prioritize investments on circular product design of valves by employing more durable materials and by increasing modularity and standardization, to reduce carbon emissions from raw materials extraction and production.
	Production process		X			
	Business Model	X				
	Supply Chain	X				
Beta	Product structure			X		Beta should prioritize investments on industrial symbiosis actions to foster the recovery and trade of its production offcuts and scraps, to reduce carbon emissions from production processes.
	Production process				X	
	Business Model	X				
	Supply Chain	X				
Gamma	Product structure				X	Gamma should prioritize investments on new business models such as leasing, to achieve a large-scale diffusion of its highly energy efficient coffee machines, to reduce carbon emissions from usage.
	Production process		X			
	Business Model				X	
	Supply Chain			X		
Delta	Product structure				X	Delta should prioritize investments on the regeneration of pallet wrappers at the end of life, facilitated through the experimentation of leasing business models, to reduce carbon emissions from end-of-life treatments.
	Production process	X				
	Business Model				X	
	Supply Chain	X				
	Regeneration				X	

Gamma should invest in the experimentation of leasing business models, to increase the diffusion of its energy-efficient coffee machines, thus lowering carbon emissions connected with the usage phase. Delta should invest in the regeneration of pallet wrappers, facilitated through the experimentation of leasing business models, to reduce carbon emissions of current end-of-life treatments of its products.

When proposing a novel tool, understanding whether the tool meets users' needs in real-world contexts is crucial. Feedback from companies was collected to assess the C-Readiness applicability. Users generally found the tool intuitive and easy to use, with a clear layout and easy-to-follow instructions incorporated within the tool. Some users highlighted that some sections required more explanation, particularly around technical terms such as industrial symbiosis and critical raw materials. Pop-up explanations with a glossary for these terms were added, making the tool more accessible for users unfamiliar with Circular Economy specific jargon. In terms of flexibility, the feedback received indicated that the questions were largely applicable to the case companies specific manufacturing context, thus showing a satisfactory level of applicability and coverage of the C-Readiness tool to different manufacturing sectors. Users particularly appreciated the web-application with the data entry features, found it quite intuitive and simple to use. Lastly, the C-Readiness scores and the positioning matrix received positive feedback in terms of insightful summaries and actionable recommendations. Users particularly appreciated the automated explanation of the results, which provides a list of pre-defined 'next steps' helping companies to understand how to effectively act on Circular Economy implementation actions for decarbonization purposes. Overall, users found the tool valuable and easy-to-use, noting that it increased their awareness of Circular Economy readiness and highlighted actionable improvement areas for decarbonization.

The novelty of C-Readiness stands in the combination of circularity readiness evaluations with quantitative LCA methodologies to identify and prioritize Circular Economy implementation actions for decarbonization purposes, as advocated by previous literature (Howard et al., 2022; Luthin et al., 2023; Rigamonti & Mancini, 2021). By looking at the circular economy literature only, it emerges that all companies should invest in the reuse and recycling of their products for preserving the

environment and limit waste generation (Kirchherr et al., 2017; Kumar et al., 2019; Okumura, 2022). However, thanks to C-Readiness, it becomes apparent that – in order to decarbonize – manufacturing companies should prioritize investments in different Circular Economy areas depending not only on their readiness, but also on the carbon footprint structure of their representative products. This aspect has not been properly considered by previous tools. By operationalizing this theoretical concept into the C-Readiness tool, this article adds fresh knowledge about Circular Economy implementation in manufacturing companies for decarbonization purposes, and provides decision-making support to manufacturing companies that start approaching the Circular Economy paradigm at an early evaluation stage.

6. Conclusion

This paper presented C-Readiness, an original and systemic tool for assessing the readiness of manufacturing companies for the Circular Economy paradigm and for prioritizing Circular Economy actions for decarbonization purposes. By addressing the limitations of existing methods and by explicitly combining circularity readiness measures with carbon footprint quantitative assessments, this paper contributes to the literature on Circular Economy implementation in manufacturing companies, providing a structured method for industrial organizations to plan and prioritize actions to reduce their environmental impact through Circular Economy.

The scientific contribution of this paper lies in overcoming the limitations of previous methods, providing a comprehensive tool for assessing Circular Economy readiness, and in offering guidance on how manufacturing companies should prioritize Circular Economy actions for decarbonization purposes. Compared to previous tools, C-Readiness not only assesses the company preparation for Circular Economy adoption, but also provides a quantitative analysis to prioritize interventions that can contribute greatly to companies decarbonization. Through the application of C-Readiness to real-world case studies, this paper also provides insights on how manufacturing companies can be supported in their decarbonization journey.

This paper also delivers relevant managerial implications.

Manufacturing companies managers interested in starting the implementation of Circular Economy can use the C-Readiness tool to assess their circularity level and to understand how to prioritize Circular Economy actions for decarbonization. The C-Readiness provides a structured path that helps them in this process. First, it helps in creating the required awareness and shared language inside the company: both are needed to embrace such a systemic transition. Then, it provides a comprehensive and structured evaluation of the circularity of a company, to understand where the company is – in terms of readiness – and where the company should work to improve circularity and decrease carbon emissions. Finally, the C-Readiness tool also entails policy and systemic implications. By applying the tool to a large-scale sample of companies within a geographical area or within a given industry, the tool can deliver a snapshot of that area or sector circularity level. Based on such information, large-scale actions can be prioritized and promoted through public policies, government interventions or industry associations measures, following a Circular Economy implementation top-down approach.

Lastly, this research has limitations. First, the tool has been purposefully designed for manufacturing companies. However, Circular Economy can be implemented also in other types of organizations and with different aggregation levels than the micro one. Future research should thus create tools specifically for service companies or for evaluation Circular Economy adoption at the meso- and macro- level (Brusselaers & Gillabel, 2024; Carissimi et al., 2023; Mendoza & Pigosso, 2023; Nußholz et al., 2023; Nyffenegger et al., 2024; Ravikumar et al., 2024). Moreover, circular readiness evaluations are based on a qualitative assessment. Although this design choice facilitates the practical application of the tool, it is less accurate than an assessment based on quantitative flows evaluations. To compute the prioritization matrix, the C-Readiness tool requires the results of a LCA study or at least an estimation of the percentage distribution of the product carbon footprint across life cycle stages. As with any LCA-based study, these results may vary depending on the quality of the input data and the assumptions made during the process. The quality of the C-Readiness indications thus highly depends on the quality of the LCA study used to fill the tool. Considering the inherent complexity of this process, and the high uncertainty that these estimations can have, users should be aware that the C-Readiness tool provides an approximation rather than an

exact measure. We thus recommend that users interpret the results as part of a broader assessment. In addition, the C-Readiness tool prioritizes Circular Economy actions by focusing exclusively on a single environmental impact dimension, i.e., the carbon emissions reduction potential. However, several other environmental impact categories require attention, since, at the time of publication, the Earth has overcome six of the nine planetary boundaries that define a safe operating space for humanity (Richardson et al., 2023). Future tools should be further developed to explore how Circular Economy can help reduce boundary transgressions across a broader range of environmental areas, to prioritize Circular Economy actions that contribute not only to decarbonization but also to other critical environmental goals.

CRediT authorship contribution statement

Gianmarco Bressanelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicola Saccani:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization.

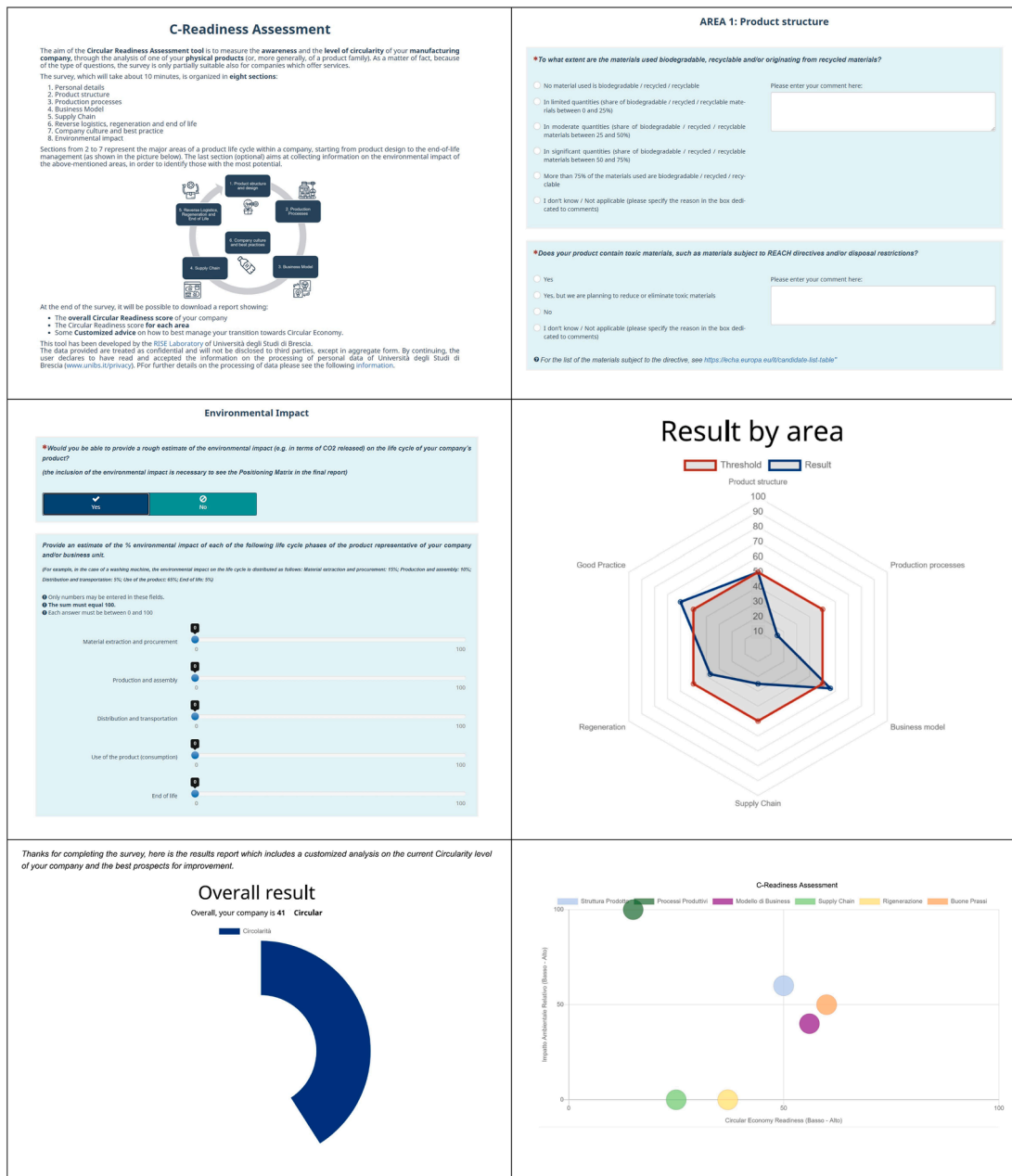
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Screenshots of the c-readiness tool



Data availability

Data will be made available on request.

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