



# Circular Economy Matrix Guiding Manufacturing Industry Companies towards Circularity—A Multiple Case Study Perspective

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## Abstract

Manufacturing companies struggle with overwhelming expectations, disruptions and trends sweeping over their business environment. The evident climate change, together with rising sustainable development goals, is forcing companies to discover their environmental impact, in addition to the more familiar economic one. The transformation from a linear economy to a circular economy (CE) reduces waste and improves resource efficiency through the deployed R-cycles, such as recycle, reuse and repair. This transformation is feasible for multinational enterprises because they can allocate sufficient resources for their strategic development goals. For small and medium-sized enterprises (SME), any additional investment must be carefully assessed and planned. Thus, SMEs need support and tools to select their next development investments. Generally, maturity models help companies find their status (compared to others) and identify the most important development areas and actions. This paper presents the CE maturity matrix, which comprises five maturity levels mapped with seven linear manufacturing value chain phases. The matrix was piloted with nine manufacturing industry companies, four of which were from Finland, one from Italy, one from Germany and three from Ireland. The CE matrix interview results showed that none of the interviewed manufacturing industry companies remained at the linearity level. The most common levels varied between systemic material management and CE thinking. In the interviews, over 40 CE actions were identified as the argument for a company reaching a CE maturity level. The transition towards sustainable manufacturing has already started but will require efforts to accelerate and to engage companies to proceed.

**Keywords** Circular economy · Manufacturing industry · Maturity model · Circular manufacturing · Sustainable development goals · Manufacturing value chain

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## Introduction

To begin with, cross-cutting topics such as sustainability and circular economy (CE) in the context of the manufacturing industry need to be clarified. Let us start with sustainable manufacturing enforced by the sustainable development goals (SDG) of the United Nations. Although sustainability has three pillars (economic, environmental and social) [1], most of the activities deployed in the manufacturing industry are still focused on economic goals. Together with the climate change, environmental aspects have been brought to the table. Still, social aspects, such as occupational well-being and ethics, are barely touched upon [2].

Also, the European Commission is pushing towards the twin transition, meaning a green, digital and resilient economy. Several related action plans have been released. These include the circular economy action plan (CEAP) [3] and the data strategy [4] to implement the European data-sharing economy, to mention two examples. Digitalisation is considered the enabler of sustainability and circularity goals [5, 6].

CE contributes mainly to environmental challenges by implementing various R-cycles, such as reduce, repair, recycle and remanufacture [7–11]. The R-cycles both solve environmental challenges and contribute to the maintenance of biodiversity. The linear economy produces (in addition to the actual product) waste after the product's usage phase. In the recycling economy, the amount of waste is already diminished, as some products or materials are recycled during the end-of-life (EoL) phase of a product. In the ideal CE, no waste is produced, as everything can be exploited within various and recurrent R-cycles, forming closed loops. Further, the industry gradually transforms from the linear economy through the recycling economy towards the circular economy when they implement new R-cycles [12]. This naturally enhances the resource efficiency of industry and enables sustainable consumption while decreasing resource usage and prolonging the resource life cycle [13, 14]. Thus, CE and R-cycles contribute to sustainability [15] especially its environmental and economic dimensions.

Indicators or concepts, such as life cycle assessment (LCA) [16], handprint [17] or footprint [18, 19], are more familiar to companies when assessing or validating their sustainability aspects. Thus, they mainly consider greenhouse gas or carbon emissions, thereby focusing mostly on the impact of CO<sub>2</sub>. Soon, big companies are requested to report greenhouse gas emissions, both on their own and from their up- and downstream value chains [20]. Low-carbon transformation requires sociotechnical transitions and multilevel perspectives [20]. The indicators may provide insight into the hot spots of the biological life cycle but do not propose development activities for the technical wing.

In 2022, the European Union (EU) promoted ecodesign and sustainable products and introduced the concept of a digital product passport (DPP). The objectives of the EU DPP are to support sustainable production, enable the transition to a CE, provide new business opportunities to economic actors, support consumers in making sustainable choices and allow authorities to verify compliance with legal obligations.

At the same time, considering the still limited adoption in the manufacturing of these circular practices [21], there is a lack of clear guidelines supporting manufacturing companies in applying this circular manufacturing paradigm [22]. Indeed, the extant literature presents contributions willing to identify or develop indicators assessing the level of circularity of products [23], processes [24] and regions [25], clarifying the current level quantitatively while limiting a prescriptive approach.

To preliminarily overcome this lack, a maturity scale for both an introspective analysis within a manufacturing company looking at the internal functions [26] and a matrix along the manufacturing value chain [27] have been developed. These maturity models, although based on scientific findings only [28], create the basement on which to start determining guidelines towards an improvement based on companies' current state. One is the elaboration of the other with a value chain perspective, and their combination reflects an artefact addressing an industrial need [29] in terms of finding the right path towards circularity. Considering the efforts already dedicated to incumbents [30] and key barriers, such as economic and technical ones [31–33], a maturity model can represent the starting point for the structured transformation of small and medium-sized enterprises (SMEs).

Nevertheless, although the maturity models, from a theoretical perspective, seem to be promising for structuring manufacturing paths, they have not yet been applied to industrial cases to prove their applicability and validity. Therefore, this contribution aims to provide a novel understanding of the actions of manufacturing companies and their (circular) value chains to extend the results coming from these two preliminary studies [27, 34] and to validate the elaborated unique CE maturity matrix, clarifying its benefits by applying it in nine industrial cases. More precisely, this contribution can be considered an extension of the work performed by Saari et al. [27], which was an elaboration with a value chain perspective on the work developed by Acerbi et al. [26]. Therefore, these two preliminary studies remain conceptual contributions based on previous literature, while the goal of the present research is to highlight the practical contributions derived from their application and validate them. More precisely, the purpose of this study is to validate the already developed maturity scale by applying it to several industrial cases, with the final goal of practical tools for manufacturing companies to pursue a path towards a circular economy.

To address this research objective, the following research question has been addressed: RQ1: “How can CE implementation activities be identified and aligned within a manufacturing company?” To address this RQ1, it can be divided into two sub-questions: RQ1.1 “What are the typical circular economy actions at different manufacturing companies?” and RQ1.2 “How are the circular economy practices aligned over different units of value chain phases?” Therefore, by employing the CE matrix [35], this research contribution, through a series of interviews held with practitioners, enables the identification of sets of circular-oriented best practices, which could be taken as references from companies to evolve towards the creation of circular systems.

Throughout this research, it was possible to grasp from practitioners the key actions, potential challenges and benefits obtainable during this transformation path. Indeed, through the nine interviews, it is expected to not only validate the maturity scales but also explore the real industrial world with its own peculiarities. This research bridges the gap between the theoretical concepts of CE and their practical implementation in manufacturing companies. At a theoretical level, the CE maturity matrix enables the recognition of companies' CE actions across different stages, from linear to circular. From a practical perspective, this research enables a valuable benchmark and the shares of almost 40 practices related to CE implementation. The structure of this contribution is as follows. Section 2 presents the research background and describes in detail the background studies used to develop the present contribution. Section 3 reports the methodology employed. Section 4 provides the results from the application of the elaborated CE maturity matrix, and Sect. 5 concludes this

paper by highlighting the key contributions to practice and theory, clarifying the limitations and the still-open opportunities for future research.

## Background

In the introduction, the relationship between sustainable manufacturing and CE is briefly examined. Sustainable manufacturing is the foremost objective and boosting the circular economy within the manufacturing industry is a tool for achieving this aim. In this section, we focus on CE and its deployment actions, i.e. R-cycles. In addition, a review of the tools available to promote CE deployment is presented. This section is finalised with a description of our CE matrix.

## Circular Economy

In this paper, we adopt the definition of a circular economy sealed by Korhonen et al.: *CE is an economy constructed from societal production–consumption systems that maximize the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows. Successful CE contributes to all three dimensions of sustainable development. CE limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction* [36].

The bottom-up CE implementation strategies for the manufacturing industry are collaborative business models, product design, supply chain and ICT [37]. The actions taken vary, and some are harder to implement. The top actions taken are the following: (i) using more sustainable materials, (ii) increasing the efficiency of energy use, (iii) using energy-efficient or climate-friendly machinery, technologies and equipment, (iv) training employees, and (v) reducing the amount of air travel. Actions such as developing new climate-friendly products or services, requiring suppliers and business partners to meet specific sustainability criteria, and updating or relocating facilities to make them more resistant to climate impacts are more complicated and harder to implement [38]. The rebound of CE also needs to be addressed, and the managerial focus should not be on simply closing material and product loops but even on reducing primary production [39].

Nowadays, limiting resource consumption is one of the main issues that manufacturing companies are struggling with, and circular manufacturing is gaining momentum and is considered a good driver in this direction [40]. To be more precise, in this context, the regeneration of resources takes place through different strategies, also called circular manufacturing strategies (e.g., recycling, remanufacturing, circular design and industrial symbiosis), which if concurrently adopted, allow support for the sustainable development of manufacturing firms [40]. These strategies might have impacts on different levels, including the micro (e.g. product, firm), meso (e.g. network of firms) and macro (e.g. nation) levels proposed by [2, 41, 42]. Although the benefits coming from this paradigm are many, including the restricted generation of pollution, waste and toxic substance emissions, the efficient use of resources and the strengthening of the connections between society and industry [43, 44], its adoption is still limited. This is because of the barriers observed [45], mainly caused by the need to establish proper information flows involving all the stakeholders along the

entire value chain, such as government, suppliers and consumers, starting from the internal companies' functions [46, 47]. Also, the sociocultural context of the entrepreneur affects the progress of the circular economy [48].

Kaupilla et al. summarised most of the R-cycles found in the literature [7] and classified them into three categories, with the lowest focusing on the useful applications of materials (recycle, recover). In the second level, the R-cycles focus on the extension of the product life cycle (repurpose, remanufacture, refurbish, reborn, repair and reuse). At the highest level, the objective includes both smart manufacturing and product usage (reduce, rethink and refuse).

## Tools to Identify Activities to Implement the Circular Economy

In this paper, we are not exploring indicators [49, 50] or concepts, such as LCA [16], handprint [17] or footprint [18, 19], but the tools and methods helping companies to implement a circular economy. Companies—especially SMEs—are struggling with disruptions and transitions and do not know how to initiate or proceed. Therefore, both academia and consultancies have provided various tools and methods to support companies through these transitions. There are methods and tools to guide companies through their digitalisation development pathways [51, 52]. In various playbooks, the applicable set of tools and methods are gathered [53–56]. Next, some available tools and indicators of circularity are introduced.

Circularity<sup>1</sup> claims to be the first CE platform. It includes assessment tools for both circularity and sustainability. It provides training for individuals at a fee. For companies, there are measurement tools and services for industrial symbiosis, in addition to consultancy. It also aims to provide tools that support reporting.

The Ellen MacArthur Foundation has been constantly pushing for CE since 2015 [57]. They introduced a CE measurement tool, Circulytics, in 2020. It supports a company's transition towards the circular economy, regardless of industry, complexity and size. Going beyond assessing products and material flows, this free company-level measuring tool reveals the extent to which a company has achieved circularity across its entire operations [58].

The circular economy toolkit<sup>2</sup> of the University of Cambridge claims to help businesses create a more sustainable future [59, 60]. The toolkit contains a free assessment tool and 10 do-it-yourself workshop kits. Also, a Nordic project—CIRCit Norden—created six workbooks<sup>3</sup>. Their tools<sup>4</sup> (in workbooks) are described with a step-by-step approach.

The World Business Council in Sustainable Development (WBCSD) has published circular transition indicators (CTI)<sup>5</sup>, a universal and transparent framework for measuring circularity, with 30 member companies. The fourth edition is a simple, objective and quantitative framework that can be applied to businesses of all industries, sizes, value chain

<sup>1</sup> Economia circolare per le imprese - Circularity.

<sup>2</sup> CE Toolkit (circularconomytoolkit.org).

<sup>3</sup> Workbooks - CIRCit Nord.

<sup>4</sup> Tools - CIRCit Nord.

<sup>5</sup> <https://www.wbcd.org/Programs/Circular-Economy/Metrics-Measurement/Circular-transition-indicators>.

positions and geographies [61]. In addition to the framework, they also provide an online tool free of charge for the companies.

Garza-Reves et al. (2019) proposed a circularity measurement toolkit for manufacturing SMEs. It covers viewpoints such as reducing environmental damage, the input of materials, critical materials and non-renewable resources and increasing internal awareness, the durability of products, external awareness, value chain support, the green market, the longevity of products, technologies and legislation development. Each viewpoint has several questions with the response options: yes, partial and no. In addition to the toolkit, they presented 36 practices from the literature [62].

Several consultancies, such as InnoGlobal, have provided sustainability maturity tools. Their digital maturity and sustainability assessment originated within the pharmaceutical manufacturing sector and is claimed to apply to all high-tech manufacturing sites. In addition to the assisted and guided self-assessments, they drafted a two-phase (service) pathway [63].

Tolstykh et al. have identified three approaches to assessing ecosystems: the micro (assessment of actors), the meso (regional, sectoral level) and the macro (global). The assessment is based on five indicators (viewpoints): density, fluidity, diversity, connectivity and entrepreneurial environment [64].

Kristoffersen et al. promote big data, data analytics and digital technologies as enablers of the smart circular economy. Further, they gathered potential CE applications to a table with three columns reflecting the life cycle phase of a product: beginning, middle and end of life. The rows indicate the smartness of the application, where the top row is the “smartest”. Smartness grows together with the focus of analysis, starting from descriptive (what has happened) and ending with prescriptive, where analytics (or artificial intelligence) may even act on behalf of the human [6]. In parallel to digital technologies, business analytics capability should also be considered when accelerating CE transition in a company [65].

Orko et al. interviewed representatives from 81 companies in three industrial sectors (textile, battery and food) to find out the importance of data, digital platforms and data sharing ecosystems when companies were considering stepping towards CE [66]. Data and sharing are expected to play a major role in the twin transition [5, 6].

In parallel with the deployment of CE activities, companies need to consider the sustainability of their businesses [67–70]. The CE Playbook is an example of a comprehensive set of tools for the circular journey that also covers the business development viewpoint [71].

Kaipainen et al. discovered how companies innovate business models and supply chains for a circular economy. They presented a framework with three levels of innovation (radical, incremental or none) and three focus areas (process, product and service). The framework clarifies whether the focus is on the meso (supply chain) or micro (business model) levels. They invite companies to start from their internal boundaries but simultaneously expand their view into their supply chains [41]. A circular business model is designed to improve resource efficiency by lengthening product lifetime through long-life design, repair and remanufacturing, and closing of material loops [68].

A systematic literature review [72] explored 16 CE maturity models where only one of them (ours) considered manufacturing companies [34], another was dedicated to remanufacturing [73] and a third was on the material flow in the supply chain. Although there are tools, methods and playbooks for CE assessment [59, 62–64, 74], deployment actions [6] and CE business model development [41, 71, 75], we propose a practical tool combining

both maturity levels and CE deployment actions within the manufacturing value chain. This practical tool—the CE maturity matrix—is briefly described in the [research method](#) section.

## Research Method

Although CE has been actively discussed in various research streams, there is limited understanding of the transition paths of manufacturing industry companies. This study aimed to provide a novel understanding of the development actions of companies and their (circular) value chains towards circular manufacturing. The study is explorative, and the case study approach [76, 77] was chosen because of its ability to help us understand emerging phenomena from the inside rather than the outside.

The main research question is formulated: “How can CE implementation activities be identified and aligned within a manufacturing company?” To address this RQ, it can be divided into two sub-questions: “What are the typical circular economy actions at different manufacturing companies?” and “How are the circular economy practices aligned over different units of value chain phases?” Our research followed the case study method, employing an embedded multilevel design with a variety of illustrative cases to describe and define the status of circularity in the context of the manufacturing industry [77]. Multiple case studies are utilised to further elaborate the actions in companies that have different roles in value chains and operate in different industries.

The maturity model (Table 1) was used as a construction for data collection (through company interviews), as well as a framework for analyses and case comparison [78]. Our analytic strategy was based on a cross-case comparison. The identification and deployment of a pathway towards sustainable manufacturing is a complex issue, especially for SMEs with limited resources. Thus, companies need practical tools to support their development. In this paper, an improved CE matrix was demonstrated with nine manufacturing industry companies, thus providing the first industrial adoption.

## Circular Economy Matrix

The CE matrix is based on the maturity levels of the circular economy generated for the manufacturing industry [26, 27]. The modified maturity levels are as follows: (i) linearity, (ii) industrial CE piloting, (iii) systemic resource management, (iv) CE thinking and (v) circularity. The maturity levels are mapped with the (linear) manufacturing value chain having the following phases: (i) product design, (ii) sourcing, (iii) production, (iv) logistics, (v) marketing and sales, (vi) product use and (vii) EoL [71]. The matrix is populated with a description of the expected actions and solutions on each cell; see Table 1 [27].

## Company Interviews

The selection of the nine case companies was made according to commonly used guidelines for case research [76]. More specifically, the research design employs a purposeful sampling strategy focusing on case study companies from Finland (equipment manufacturing), Ireland (food manufacturing and waste treatment) and Italy (textile manufacturing). The rationale for this selection is twofold. On the one hand, these companies are embedded contextually

**Table 1** CE maturity levels mapped with the linear value chain improved from [27]. The potential R-cycles appear in bold in the relevant cells

Units of the linear value chain	Linearity	Industrial CE piloting	Systemic resource management	CE thinking	Circularity
Product design	Product design does not consider durability, upgradeability, circularity or sustainability.	The company considers the transition from the use of unsustainable and hazardous substances to sustainable raw materials. The company has piloted the <b>repair or reuse</b> of products. <b>Refuse</b>	Durability and upgradeability of products are promoted and applied. The personalisation of products is driven by demand and purpose. <b>Prethink</b>	Environmental impact assessment is a driving force of product development (ecodesign). Products are designed to avoid loss and premature end-of-life. <b>Prethink</b>	Products are fully circular by design, enhancing purpose-based durability during the life cycle and enabling multiple <b>reuses, repairs, refurbishments, remanufacturing</b> and regenerative <b>recycling</b> at end-of-life.
Sourcing	No actions to reduce the consumption of energy and/or materials are being implemented. Materials are sourced based on performance and price.	The company seeks to minimise inputs of energy and materials. Material sourcing is being shifted from unsustainable to sustainable raw materials. <b>Reduce, reuse</b>	Sourcing is based on code of conduct guidelines for circularity and the sustainability of materials. The amount of waste is minimised and side streams are utilised. <b>Reduce, reuse, recover</b>	Raw materials are sourced mainly from known and monitored secondary markets and through reverse logistics. Social impacts are considered in the sourcing process. <b>Prethink, recover, refuse, reduce</b>	Full circularity is enabled by sustainable materials that have less environmental impact (on biodiversity, climate change, acidification, etc.) than their traditional counterparts. <b>Recycle, recover</b>
Production	The company's operations meet environmental regulations, but R-cycles are not considered.	The minimisation of virgin raw materials, water and energy has been piloted at machine, process and company levels. <b>Reduce, refuse</b>	Production-on-demand allows the company to limit inputs and reduce outputs, avoiding unnecessary use of raw materials, water and energy. <b>Refuse, reduce</b>	Circular production scheduling considers stocks on different levels. <b>Remanufacture, refurbish</b>	Production is environmentally sound, which is enabled by close monitoring of the environmental impacts of production processes. <b>Reduce, reuse, recycle</b>
Logistics	The company has no goal of optimising logistics.	Logistics optimisation pilots are taking place. <b>Reduce, rethink</b>	In addition to deliveries, logistics covers raw materials, waste and used products. <b>Reduce, reuse, rethink</b>	Linear and reverse logistics are considered with partners. Traceability of products is implemented. <b>Reduce, reuse</b>	Value chains are localised, and closed loops are implemented. Transparency of products, production and logistics is enabled. <b>Reduce, reuse, recycle</b>



**Table 1** (continued)

Units of the linear value chain	Linearity	Industrial CE piloting	Systemic resource management	CE thinking	Circularity
Marketing and sales	The company has not included CE sustainability viewpoints in its marketing activities.	Communication of CE piloting activities is planned as part of strengthening the company's image. Preliminary footprint calculations are exploited. <b>Rethink</b>	Materials origins, workforce and locations are communicated transparently. The reception of used products is organised. <b>Reuse, recycle, rethink</b>	Proactive demonstrations of sustainability activities on the environmental, social and economic levels are capitalised. Transparent LCA or footprint calculations. <b>Rethink</b>	Proactive handprint is transparent and describes the expected positive environmental impacts. <b>Rethink</b>
Product use	Products are not reused or repaired during their life cycles.	Pilots are undertaken for reuse and for the recovery of materials from used products. <b>Remanufacture, refurbish, repurpose</b>	Production plans are based on an analysis of multisource product usage data. <b>Repair, reuse, remanufacture, repurpose, refurbish</b>	Prolonged life cycle, upgrades and repairs to products are enabled. <b>Repair, reuse, refurbish, remanufacture</b>	Sharing economy business models provide novel alternatives for product usage maximisation. At the EoL phase, <b>reuse, remanufacturing, repair, refurbishing or recycling</b> is enabled.
End-of-life	At end-of-life, the product is treated as waste.	Pilots are undertaken that upgrade materials or products for <b>reuse, Remanufacture, refurbish, repurpose</b>	<b>Reuse</b> of products, side flows and waste are implemented. <b>Remanufacture, refurbish, repurpose, recycle</b>	Environmental, social and economic impacts of end-of-life products are known. Zero-defect goal. <b>All Rs</b>	The next life cycle of a product is known, with its environmental, social and economic impacts, emphasising the zero-defect goal and positive environmental impacts. <b>All Rs</b>

in countries that have developed recognised circular economy strategies, with particular emphasis on the industrial sectors they represent [79–81]. On the other hand, the chosen companies are forerunners in the circular economy within their respective industrial sectors. By focusing on these leading firms, this study develops insights into the cutting-edge approaches and challenges encountered in implementing circular economy principles. In the cases, the researchers had access to the strategic development agendas, and the selected cases were both comparable and complementary, i.e. they present different value chain roles within manufacturing ecosystems.

The CE matrix was validated with nine manufacturing companies (Table 2), from which two were multinational enterprises (MNE) and five were small and medium-sized enterprises (SME). In addition to four Finnish metal fabrication companies, two textile manu-

**Table 2** The manufacturing companies interviewed with the CE matrix

Com-pany ID	Country	Size	Role	Industry domain
A	FI	MNE	global	28 Manufacture of machinery and equipment
B	FI	MNE	global	27 Manufacture of electrical equipment
C	FI	SME	sub-contractor	25 Manufacture of fabricated metal products, except machinery and equipment
D	FI	SME	sub-contractor	25 Manufacture of fabricated metal products, except machinery and equipment
E	IT	SME	national	13 Manufacture of textile
F	IE	SME	national	10 Manufacturing of food products
G	IE	SME	global	38 Waste collection, treatment and disposal activities
H	IE	Non-profit organisation	national	38 Waste collection, treatment and disposal activities
I	GE	Start-up	national	13 Manufacture of textile

**Table 3** Status of CE matrix discussions and the roles of the attendees

Company	Status	Senior manager	Middle manager	Expert
A	completed	3		
B	completed		1	
C	completed		2	1
D	completed		1	
E	completed			1
F	completed	1		
G	completed	1		1
H	completed		1	
I	completed		1	
9 companies	9 sessions	5	6	3

facturing start-ups—one Italian and the other German—contributed to the validation. From Ireland, a food manufacturer and two waste collection companies were included.

The data utilised included interview data, development plans of companies and background material, such as their web pages. Table 3 presents the details of the company interviews in terms of the roles of the participants and the dates of the interviews. The interviews were organised remotely. Interviewees facilitated the session, displaying the CE matrix in MS Teams and highlighting the assessment by green colour. In addition, the notes were written by the interviewees. The time reserved for each company interview was 1.5 h. At its shortest, the matrix was covered in an hour and the company received its assessment of its CE maturity level as a map.

Both companies A and B are big manufacturing companies in Finland. A produces machinery and equipment, while B contributes electrical equipment. Both A and B have considered the economic viewpoint of sustainability in terms of efficiency and cost reduction for decades to keep their businesses competitive. The interviews focused on one business area of the company and did not give an overall picture of the MNE. Both companies have several sites in Finland and abroad.

Companies C and D represent Finnish SMEs that are producing fabricated metal products, mainly for some original equipment manufacturers (OEMs) that are also MNEs. They do not (themselves) export their goods, being components of OEM-owned products. They struggle when contributing to the SDGs and overcome their challenges mainly with efficient production and energy-efficient facilities.

Company E is a start-up operating in the textile industry located in Italy. More specifically, it manufactures clothes and other garments based on organic biomass. It supplies fashion brands with the textiles they produce.

Company F uses underutilised solid side streams from the Irish agri-food industry that typically either must be disposed of or sold off at a marginal cost. Working with agri-food and biotech companies, it converts side streams into high-value, functional ingredients, protein and nutraceuticals through a low-energy, low-water, large-scale, solid-state fungal fermentation process. Examples of converted side stream applications include enhanced flour for bakery products, pasta, noodles and meat extenders.

Company G is an Irish cloud-based technology platform designed to enable households to recover and reuse postconsumer products and materials. Focused on reverse logistics, it consists of linked user and driver user apps, making it possible for end users to register collection requests from their own homes.

Company H works with collection partners, recycling facilities and specialist downstream processors in Ireland to manage hazardous waste and recover resources. In a pilot development, it identified and isolated modules from existing waste lithium battery flows intended to stabilise and repurpose waste batteries for alternative applications as second-life energy storage batteries. I is located in Germany, and it operates in the textile industry, being a made-to-measure brand for women. The company relies on the core principles of CE, and it provides personal tailor consultancy with the support of virtual 3D design to perfect-fit the customer and foster sustainable and circular material innovation.

Table 4 presents the CE matrix template, which was filled in cooperation with the company representatives interviewed. The green cell is a jointly agreed-upon assessment that was explained and instantiated with reasoning that illustrates the demonstration of the level. Usually, actions were identified at either the higher or lower level. These were documented briefly on the map (Table 5).

**Table 4** CE matrix template

	Linearity	Industrial CE piloting	Systemic resource management	CE thinking	Circularity
Product design				Reasoning	
Sourcing			Some actions remain on a lower level		
Production				Some actions reach a higher level	
Logistics					
Marketing and sales					
Product usage					
End of life					

**Table 5** Summary of companies' CE matrix results

	Linearity	Industrial CE piloting	Systemic resource management	CE thinking	Circularity
Product design		G, H	B, C, D	A, F	E, I
Sourcing		B, H, I	C, D, G	A, F, E	
Production		E, G, H	A, B, C, D	F, I	
Logistics		B, H	E, I	A, C, D, G	F
Marketing and sales			A, B, C, D, G, H	F, E	I
Product use		E, G, H	D	A, B, C, I	F
End of life		E	A, B, C, G, H		F, I

## Findings

In this section, the anonymised CE matrix results of the interviewed companies are presented, along with the reasoning for each value chain phase. Further, a condensed summary table of the CE actions is discussed.

### CE Matrix Interview Results

The CE matrix results of the interviewed companies are summarised in Table 6. The good news is that according to our study, none of the companies remained on the linearity level. There are several phases (sourcing, production, logistics, use and EoL) where pilots are ongoing instead of systemic resource management. Further, there are already several hits to the circularity level, in phases such as product design, logistics, marketing and sales, product use and EoL. Still, the most popular level is systemic resource management, and CE thinking is as follows.

In **product design**, companies G and H perform at the level of industrial CE piloting. Company G provides electronic waste collection services and processing for the reuse or recycling of electronic home appliances, and company H, via a demonstration project, has identified and isolated modules from existing waste lithium battery flows for the refurbishment and reuse of undamaged modules. Three companies B, C and D fall into the systemic resource management level. Company D promotes and applies the durability of its products. Company B listed the durability, upgradeability and personalisation of the electronic equipment as the reasoning for the systemic level. Companies B and C are also considering disassembly and are thus already tapping the CE thinking level. Material and energy efficiency are important design parameters for every company. Company A reaches the CE thinking level and aims for the circularity level, as their metallic products can be repaired, remanufactured, refurbished and reborn. Furthermore, 98% of the weight of their products is recyclable, as the material can be melted down. For company F, the environmental impact assessment is a driving force of the food item and component development. Components are

**Table 6** CE actions mapped with value chain phases based on company interviews, where (X) indicates the phase in which the action is more strongly manifest and (\*) indicates the phase in which the action also performs an ancillary role

Actions mapped / Phase	Product design	Sourcing	Production	Logistics	Marketing and sales	Product usage	End of life
Design for durability, longevity, reusability and upgradeability	X				*	*	*
Design for disassembly, repair, remanufacturing, refurbishment and reborn	X				*	*	*
Design for energy and material efficiency, e.g. recyclability of valuable materials	X	*			*		
Personalisation of products to better align with customers' requests and expectations (on-demand production)	X				*		
Social impact assessment of suppliers		X			*		
Environmental impact assessment of suppliers		X			*		
Establish partnerships with certified entities		X		*			*
Reverse logistics to organise the return flow		X		X			*
Recycling either internally or relying on external partners		X			*		*
Transparent supply chain		X	*	*			
Production scheduling and even on-demand production			X	*	*		
Sourcing raw materials from EoL phase products		*	X				*
Closed loop for water and chemicals			X				
Continuous improvement according to ISO 14,001 standard			X				
Monitoring of energy consumption			X	*			
Monitoring of environmental impacts			X				
Certified subcontractors		*	X				
Ecodesign principles	*		X				
Reselling of remanufactured products			X				*
Minimising waste with partners			X	*			

**Table 6** (continued)

Actions mapped / Phase	Product design	Sourcing	Production	Logistics	Marketing and sales	Product usage	End of life
Gathering trusted data from logistics				X			
Requesting electric vehicles				X			
Piloting product management system to enable the reuse of products			*	X		*	*
Sustainable packaging with minimum waste				X			
Sustainable transportation options				X			
Minimised transportation or local value chains				X			
Transparency of products and production characteristics	*	*	*	X			
Product-as-a-service business model	*			X			
Collecting data on materials, workforce and sites and providing visibility for the social pillar of sustainability,		*	*	*	X		*
Piloting for brand image LCA and footprint calculations		*	X		X		*
Consumer engagement in the innovation process	*				X		
Lengthening the product lifetime by updating, repairing and producing initially high-quality, durable products	*					X	*
Maintenance service						X	
Providing consumer applications to enable the consumer to maintain product quality						X	
Returning product on the EoL threshold via reuse, refurbishment or repurpose strategy						X	*
Extension of product lifespan and value through business model innovation						X	*
Reuse of products, side flows and waste			*				X

produced to avoid the loss of food manufacturing side streams, which are redeveloped into components for within- and cross-sectoral uses. Company I, being a start-up born from the very beginning to be circular, has its product design at the highest level since it is based on principles of ecodesign and enhancing product longevity and reusability, while also minimising waste in pattern making. Further, 3D design software is used to help clients visualise the final garment and receive exactly what is desired and expected, putting great value on long-lasting designs and production. Additionally, a precise client-like avatar was created, with the exact measurements taken to effectively cut fabrics and make a perfectly fitting garment, avoiding additional waste. The circularity level is also occupied by company E, as their manufacturing process starts from the upcycling of organic biomass recovered from industrial waste flows to substitute virgin raw materials of viscose, lyocell and acetate fibres. The resulting fabrics are designed to contain only blends with other sustainable fibres and are certified to be recyclable and biodegradable in all environments when the final life stage of the fibre is reached.

In **sourcing**, the most populated level is CE thinking (A, F, E), but three companies were levelled up to the industrial CE piloting level (B, H, I) and two others to the systemic resource management level (C, D). Company B selected the piloting level although their mineral sourcing is already systemic, and the social impact is caught via the environmental programmes of the supplier. In company H, long-life lithium batteries are sourced from electric vehicles, mobility applications, IT and energy storage systems, which have reached the end of their first life. The same level, the piloting one, was selected by I since it selects supply chain partners based on their location (locally sourced certified natural), standards and sustainability levels to build long-lasting relationships, developing additional value from co-innovation synergies by redefining material mixes also at the yarn and fabric level, introducing new more fitting designs to align to what the clients and the fast-changing market are looking for, and avoiding unsellable stocks. Companies C, D and G select systemic resource management as the amount of waste is minimised. Both companies C and D pursue higher levels, as raw materials are sourced mainly from known markets and sustainable materials (C) or social impacts (D) are considered. Company G provides collection services directly from households through reverse logistics. Company A reaches out to the CE thinking level, as the social impacts are also considered by following the sourcing and conflict minerals instructions. Still, no reverse logic is implemented (by A itself), as their customers (abroad) organise recycling independently. The same level was chosen by company E because the transparent and traceable supply chain of manufacturers and outsourcing partners is carefully monitored and selected to respect high environmental standards and high-quality production to reach high product performance and longevity. Company F justifies the CE thinking level, as the side streams of the food manufacturing industry are sourced from known and monitored markets and through reverse logistics. The social, economic and environmental impacts are also considered in the sourcing process. Finally, although no company was assessed at the linearity level, one company confessed that the materials are sourced mainly based on performance and price.

In **production**, most of the companies were assessed at the systemic resource management level. Three companies (E, G and H) selected the piloting level. Company G minimises electronic waste through partnerships with disassembly, rescue, repair and redistribution. In company H, long-life lithium batteries are sourced from electric vehicles, mobility applications, IT and energy storage systems, which have reached the end of their first life. In

company E, the LCA has been carried out and process improvements have been tested to recycle process water and chemicals in a closed loop and minimise energy requirements without involving external entities and systemically performing the LCA. Established manufacturing companies usually have ISO 14,001 environmental management systems (2015), and production is subject to continuous improvement. Usually, the loss of the production process is monitored. In addition, emissions are monitored in company A. Further, energy consumption data collection (A, C) or monitoring of environmental impacts (B, C, D) is on the development agenda. Company I positioned itself at the CE thinking level since the production is carried out in an on-site lab and by selected manufacturers (in Portugal and Italy) with high sustainability standards and certifications. Further, the production is highly integrated with the ecodesign principles adopted and that help to develop garments that are easy to reconfigure, reuse and recycle in a closed loop. Additionally, the products that are brought back can be easily reconfigured and sold again. Company F was also positioned at the CE thinking level, as its production scheduling considers stocks on different levels, avoiding the unnecessary use of raw materials for component development.

In **logistics**, there is more variation, as only the linearity level remained without any hits. Company B chose the piloting level because it did not trust the data and forecasts provided by the logistics partners. In an interesting detail, they were requesting electric trucks. Company H was also assigned to the industrial CE piloting level, given the focus of its pilot on developing a long-life lithium batteries management system that enables the secure removal, collection, sorting and discharging of waste batteries. In turn, company I was positioned at the systematic resource management level since attention is given mainly to the most sustainable packaging and transportation options, which need to be environmentally friendly and waste minimising. The same level is occupied by company E since raw material and waste transportation are minimised thanks to co-location strategies. Further, outbound logistics are optimised to minimise shipping and choose lower emissions options. Four companies reached the CE thinking level because the traceability of products was implemented (A, C, D). In this phase, the highest level, circularity, is touched by a few companies, as the value chains are local (A, C, D), transparency of products and production characteristics are enabled (D) and product-as-a-service business models (A) are employed. In addition, the level of CE thinking is attained by company G, given that linear and reverse logistics are considered with partners. Company F settled on the circularity level, as reverse logistics is considered with partners, the traceability of products is implemented and value chains are localised.

**Marketing and sales** remain at the systemic level of the above. Although the systematic level is mostly selected, company A states the origin of the materials, workforce and production sites mainly for quality reasons. Further, in company A, the reception of used or returned products is not arranged, as the customers organise it themselves. The reasoning for CE pilots is brand image (B). Company H attains the systemic resource management level, as the pilot created an opportunity for a long-term solution for the dismantling and recycling of electronic vehicle batteries. The carbon footprint is reduced by minimising the volume of exported materials. Positioned also at the systemic resource management level, company G emphasises transparent communication of the origin of materials, which is optimised by the platform they manage. In four companies, the CE thinking level is nearby because of customer-specific footprint calculations (A), sustainability demonstrations implemented (C) or considered (D) together with LCAs and transparency used to communicate supply chain



partners, sustainability gaps and improvements, textile certifications, sustainability assessment, special projects and start-up competitions (E). Company F reaches the CE thinking level as the proactive demonstrations of sustainability activities are capitalised, with transparent communication of side streams origin. Only company I is positioned at the circularity level since they offer transparency about the supply chain concerning suppliers, materials used and sustainability certifications and assessments to their clients. Digital consultancy, together with the yearly events that are organised for their consumers, facilitates the inclusion of consumers in their innovation process and limits potential emissions and waste generation. In addition to L, a circularity level is pursued because a positive handprint is a common goal with partners (of companies B and C).

**Product usage** is on the CE thinking level in four companies (A, B, C and I), as the extended life cycle of the product is realised by updating and repairing the products during their usage but also by producing high-quality long-lasting products. Company D leaves the CE thinking level to its subsidiary, having its own products with prolonged life cycles via upgrades and repairs. Two companies chase the circularity level as the maintenance contract business models based on the usage of a product are offered (A) or considered (C). Companies E, G and H instead still occupied the industrial piloting level. In company E, although product longevity is a key driver for sustainability, preliminary actions have been carried out to influence better use applications and care of the fabrics. In company G, electronic waste is recovered primarily for refurbishment and reuse. Similarly, in company H, waste batteries are repurposed as second-life energy storage batteries. Company F reaches the circularity level as the development of food manufacturing components is prompting business model innovation at the level of service platform development, with bioconversion activities operationalised through technology transfer, licensing and revenue sharing.

The end-of-life (EoL) phase remains at the systemic resource management level in most companies (A, B, C, G, H), as during the EoL, the products, by-products and waste are reused. Although the environmental, social and economic impacts of EoL products are known in these metal fabrication companies, this phase remains systemic as zero defect is not the driving target, except in company C. Company D totally skipped this phase, as they considered it inapplicable to subcontractors. In company G, the reuse of electronic home appliances is implemented. Similarly, in company H, long-life lithium batteries are tested, stabilised and repurposed for alternative applications, i.e. power storage systems. Company I is positioned at the circularity level since they incentivise their consumers, also economically through discounts or updates of their old clothes, to bring back the used products. In this manner, they can perform an LCA assessment and maintain control over the clothes for proper EoL management. Also, company F stressed the circularity level as the next life cycle of a component developed from an agri-food side stream is known, with a mapping of environmental, social and economic impacts. Instead, company E is positioned at the piloting level since tests about different biodegradability conditions and recyclability are being carried out and closed-loop circular strategies are being put in place to return the products and dispose of them in the most environmentally sound way, respecting the waste hierarchy and maximising circularity potential.

To sum up, the identified actions at this EoL phase were dependent on the companies' role in the value chain. The subcontracting company considered that it was not able to contribute to this phase. Similarly, most manufacturing companies have limited actions at this phase although the reuse of products, side flows and waste were partially implemented. Two

companies had intentional actions for reuse and circularity of their products, and they were identified at the circularity level of the matrix.

### Condensed CE Actions

Table 6 responses to the research questions. The actions requested in RQ1.1 appear as rows in Table 6. The actions were collected from the reasonings the company representatives gave during interviews and were reported within the value chain phases in the paragraphs above. Further, the applicable value chain phases of RQ1.2, are expressed in the columns. During the interviews, the company representatives were eager to report all related CE actions even though they might apply (better) to other phases. Thus, the actions identified by company representatives are expressed with “X” and the interpretation of additional phases done by researchers by “\*”. In most cases (action rows), the X also indicates the most prominent phase where the action applies. The interviewed companies might have been slightly over-representative when reporting their actions. Thus, the phase of the action might not be fully aligned with the moment and phase of the interview. For example, the two topmost actions in Table 6 for sure deal with the product design phase as identified by the companies but can also be exploited in marketing and sales. Durability lengthens the lifetime of a product; thus, the product usage phase can be mapped. Further, reuse takes place in the EoL phase. On the second row, repair takes place during product usage, while remanufacturing, refurbishment and reborn are actions done when returning the product to use.

Reverse logistics (eighth row from the top) has two Xes because the two companies recognised the same action but at different phases. In addition, reverse logistics deals with EoL, as the used products are collected after the actual usage of the products. Thus, most stars result in the words and meanings of the action.

LCA and footprint calculations represent a different kind of case because the calculations have led to actions such as (i) organising the collection of used products with external actors (EoL), (ii) dismantling and recycling of products (EoL) and (iii) minimising the volume of exported materials (sourcing).

Transparency was a topic that emerged in three actions: (i) transparent supply chain (sourcing, production and logistics), (ii) gathering trusted data from logistics (logistics) and (iii) transparency of products and production characteristics (design, sourcing, production and logistics). The actions were not merged as the object of transparency—data to be shared—varied, as did the phases in which companies reported their transparency actions. The interviewed companies did not mention the concept of digital product passport (DPP) although it aims towards transparency and will be requested for any key product entering European markets in future<sup>6</sup>.

## Discussion

Dominant perspectives on CE tend to present CE transitions as a practice-oriented industrial model that has the generative capacity to address global sustainable development challenges. This is aligned with an ecological modernisation discourse that champions technological

<sup>6</sup>[https://ec.europa.eu/commission/presscorner/detail/en/ip\\_23\\_6257](https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6257).

advancement as a vehicle for developing solutions to socio-environmental problems [2, 8, 37, 42, 82].

The emphasis on technological advancement has placed CE practices and their *de facto* ability to produce environmental benefits under increasing scrutiny, particularly at the levels of natural entity use reduction, waste reduction, and climate change impacts [2, 39, 68, 70]. In line with this, all interviewed companies emphasised the importance of resource efficiency, and most of them were positioned at the systematic materials management level. It has also prompted companies to rethink the design of products and technological improvements in ways that deal with the complexity of reconciling rising demand for goods and services while minimising waste quantities [14, 20], as done by company I.

The onus of embedding circular economy practices into business models is placed upon companies, but the actions required to operate as eco-innovators or to adapt value chain networks are complex and nuanced [67, 68]. Similarly, the interviewed companies identified a limited number of practices that considered the whole value chain. In other words, companies were seldom positioned at the fifth level of the CE matrix. For example, reverse logistics and maintenance services companies have to collaborate with other companies [28]. In addition, information throughout the supply chain has to be collected for transparency and, more precisely, for the DPP.

The translation of such expectations into concrete actions requires a scaffolded process, which we propose in the form of a maturity matrix that represents positions or dynamic states in a continuum of actions towards a structured transformation pathway. In this sense, the CE maturity matrix presented in this article addresses the challenges posed by the acknowledged difficulty associated with the multiplicity of interpretations concerning the circular economy and how this engenders tensions in policy expectations and concrete actions [2, 13]. The proposed CE maturity matrix does not claim to solve all areas of tension, but it illuminates the practicalities of developing circular economy business models, which are often missing from the circular economy literature [33].

Collecting the CE actions of companies (Table 6) resulted in a total of almost 40 actions identified in the value chain phases. Most of the actions are interconnected over the phases, thus influencing more than one phase. Although several tools were introduced in this paper (including our CE matrix), the tools do not help companies find the most actionable and impactful actions when they struggle with resources and have to balance their development actions with business. A holistic approach to business analytics is needed when leveraging data and analytics towards a more efficient and effective digitally enabled circular economy, the smart circular economy [65]. An assessment tool for future CE actions could be beneficial for companies. From the action list, we noted that at least LCA and footprint calculations led to other CE actions for the enhancement of the calculation results. An old truth—you will get what you will measure—still requires attention.

Our method (CE matrix) also received feedback. Company A was extremely delighted with the discussion because it also has its own ongoing sustainability development programme. This might be the reason to allocate three senior managers to our remote interview session. They also stated that benchmarking between companies is important, as is the sharing of best practices.

For the MNEs, the assessment was slightly painful, as nobody can assess the operations of a company as a whole. The focus had to be maintained in one's own business unit, even if one knew that the neighbouring unit was already somewhere further ahead. In addition,

in the MNEs of one business unit may be the customer of another. In this case, the customer is internal, and marketing was not considered so important. SMEs also consider marketing unnecessary, especially in cases where they have one strong customership with an OEM. Further, the SMEs (suppliers) struggled with the product design phase, as they did not have their own products (to be designed) but produced/manufactured whatever was ordered. One supplier declined to consider the EoL phase of the product, as it did not have visibility of the product once it was delivered to the OEM. The SMEs were keen to define the role of sub-contractors (in a value chain). In addition to the sourcing, production and logistics phases, they can contribute (towards sustainability) only with the resource and energy efficiency of their (production) facilities. Sustainability is not only in terms of material and product choices but also in terms of rethinking the social, economic and technological structures, procedures and systems that are used to underpin business-as-usual in existing linear business models [2, 32, 36, 37, 42]. These viewpoints should be reconsidered in terms of proactive impact monitoring and servitisation potential, as well as reducing material use and embedding practices of efficiency and process optimisation [69].

The butterfly of sustainable manufacturing [57] has an additional wing: information [75]. Data, information technologies and digitalisation will act as an extra sail (spinnaker) and enable a smooth and sustainable twin transition [5, 6]. Trust and security are essential when gathering and sharing data along the manufacturing value chain and product life cycle. Data spaces and DPPs have been discovered in several ongoing ventures. In addition to federated data sharing, digital twins, AR/VR and metaverse will be harnessed for sustainability. For a sustainable twin transition, joint actions and collaboration between companies will emerge [27]. Collaboration platforms can support diverse stakeholders to innovate and scale sustainable solutions for the welfare of both people and the planet [83].

## Conclusion

In addition to the resiliency issues caused by global uncertainties, manufacturing companies are forced to proceed with the SDGs. CE enhances resource efficiency while companies are implementing R-cycles such as recycle, reuse and remanufacture. Thus, CE contributes to two out of the three sustainability pillars—environmental and economic—and leaves out the social aspects.

For this paper, we interviewed nine manufacturing companies, with our CE matrix having five maturity levels and six (linear) manufacturing value chain phases. The matrix is populated with the expected CE actions and the result map for each interviewed company was created during a remote session taking about 1.5 h.

The interview results claim that every company has started its journey towards sustainable manufacturing, as there are no hits on linearity. The most popular CE maturity levels were systemic resource management (with 19 hits) and CE thinking (16). The circularity level was reached by SMEs and start-up companies that based their business logic purely on the circularity of either food or textile manufacturing. One start-up company tamely selected the industrial CE piloting level, as it had just piloted the technologies, but it had not yet been exploited, as the company was newly established. According to our results (which have a limited sample of companies), it seems that the established metal fabrication companies fall behind the start-ups designed for CE.

In some cases, the positioning of a company was surprising. An example is when company I proposed tracing the origin and supply chain actors to provide transparency for the customer, i.e. for phase marketing and sales instead of logistics. We need to note that the assessment of companies took place together with the company representatives and that the authors did not wish to change their opinion although the reasoning was discussed. Thus, company results are subjective although co-created.

The matrix helps companies find out what kind of actions to proceed with but does not provide examples of technical implementation or success stories. Companies consider benchmarking relevant and are keen to know the best practices of peer companies. Currently, our matrix is manual, and the results are compiled in an interview with the authors. It would be interesting to implement the tool as a web service. The next step would be to populate the matrix with the implemented success stories of companies so that similar entities might take these actions as inspirations for their current businesses. Also, the impact assessment tool for the planned action could be investigated.

A start-up company bases its business model on advanced digital technologies, such as 3D visualisation with avatars, harnessed towards the sustainable product development process. In addition to their own sophisticated product development, they also exploit the capability of supply chains to collect and provide qualified recycled materials for remanufacturing.

Another interesting topic is the relevance of data and data sharing. What kind of data enables the implementation of new R-cycles? What is the DPP going to look like? Will its implementation promote CE or deploy SDGs? As further research, we aim to determine the minimum viable data content of DPP that supports sustainability but does not maximise the costs and energy consumed in data management or telecommunication.

Tracing product origin, material or supply chain is a complicated issue. When talking about (small) standard parts (such as screws), it is hard to know where they come from. Still, they might contribute to the final sellable product of the OEM, being very tiny things on the whole. The implementation of DPP driven by the EU must be tackled with secure aggregated big data linked to the product.

Further, companies are struggling with their role of business and corporate social responsibility: profits can be lower to safeguard labour rights, human health, civil liberties, environmental quality, sexual equality and social justice [84]. Although the existing CE research mainly focuses on the technical levels of the actual physical flows of materials and energy in production–consumption systems while leaving values, societal structures, cultures, underlying worldviews and the paradigmatic potential of CE largely unexplored [82], we will leave the analysis and inclusion of social dimensions for future research where the CE actions will be investigated along with the value chain and workforce management practices.

In terms of implications, the research contributes to bridging the gap between the theoretical concepts of CE and practical implementation in manufacturing companies. At a theoretical level, the CE maturity matrix offers a novel, detailed framework for categorising a company's CE efforts across different stages, from linear to circular. From a practical perspective, our study suggests that companies value benchmarking and sharing best practices related to CE implementation, which the CE framework enables, alongside a detailed collection of practices across all stages, which they can mobilise to advance their CE maturity pathways. Therefore, the CE maturity matrix operates as a tool for companies to self-assess their CE journey, identify areas for improvement and identify archetypical practices at each

stage. In terms of limitations, the findings encourage further development of the CE matrix to include success stories and practical examples for implementing CE actions but also a more in-depth consideration of data management considerations, as well as the exploration of social responsibility aspects within the CE framework.

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## Declarations

**Conflict of Interest** The authors declare that they do not have any conflicts of interest.

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