POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

The Circularity Balanced Scorecard: A tool to integrate the Circular Economy into corporate strategy

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

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ACADEMIC YEAR: 2023-2024

1. Introduction

In recent decades, industrial activities have significantly contributed to climate change, causing severe environmental damage and negatively impacting human well-being. This situation underlines the pressing need for a shift in the current economic paradigm in order for it to become more respectful of the Earth's biocapacity. Sustainable Development (SD) and the Circular Economy (CE) are two paradigms that could tackle these problems: despite diverging in terms of objectives, stakeholders, and timeframes, the two are closely linked since the CE is a means to achieve SD. The Circular Economy aims at decoupling economic growth from resource consumption and mitigate negative environmental impacts and it is grounded in the following principles: design out waste and pollution, circulate products and materials, and regenerate nature.

For companies, having a well-organized Performance Management System (PMS) is essential for both internal and external purposes: Key Performance Indicators (KPIs) aid in goal-setting, aligning with organizational strategy, monitoring performance, and benchmarking against competitors. Additionally, despite the growing significance of the Circular Economy concept, there is a lack of a structured and comprehensive approach to micro-level CE measurement, hindering companies and organizations from gaining a strategic understanding beyond isolated initiatives.

According to these premises this Dissertation has the objective of filling this gap by creating a model that helps companies integrate the CE into their PMS.

2. Literature Review

The Literature Review of the Dissertation follows two main research lines: one on the Balanced Scorecard, aimed at giving an introduction to the traditional Balanced Scorecard model and at gathering existing knowledge on innovative and sustainable Balanced Scorecard architectures, and one on the Circular Economy, with the objective of presenting the state of the art in literature about CE strategies, metrics and maturity levels.

2.1. Balanced Scorecard

The Balanced Scorecard is a Performance Management System, introduced by Kaplan and Norton in 1992 [1], and later revisited in 1996, based on the idea that neither financial measures nor operational measures alone are enough to have a good picture of the performance of a company: the BSC is divided into four perspectives measuring the company performance from different standpoints, each of which, in the authors' opinion, should be articulated in four to seven indicators.

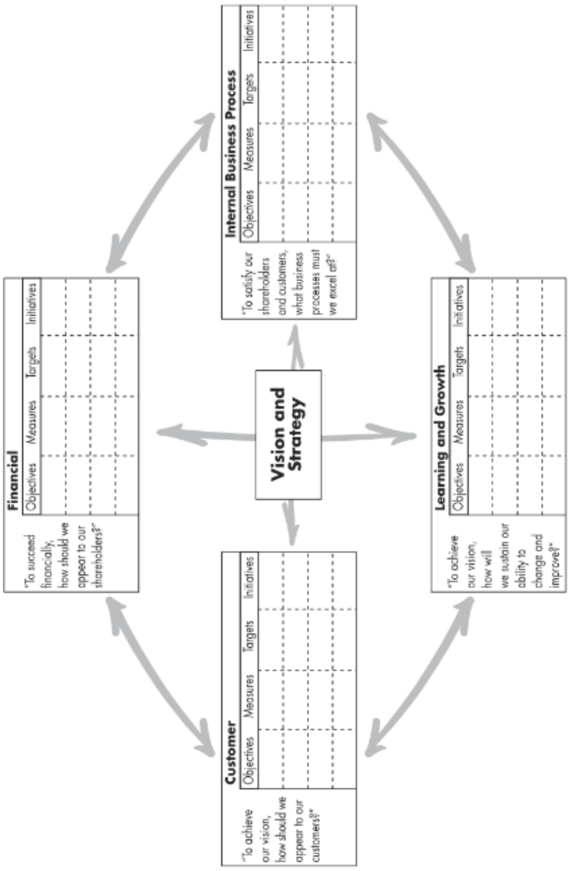

Figure 1. The four perspectives of the Balanced Scorecard

The four perspectives (as per Figure 1) are:

- Financial ("How do we look to shareholders?")
- Customer Relationship ("How do customers see us?")
- Internal Business Process ("What must we excel at?")
- Learning and Growth ("Can we continue to improve and create value?")

This allows the BSC to give a complete view of the company's performance while keeping an orderly organisation and, depending on the structure adopted, to link the indicators among themselves, thus providing a clear bottom line result.

The BSC, therefore, is not just a way to measure performance, but it is also a way to clarify, update, and internally align the company's strategy: this has made it a very widespread instrument, both in academia and in companies.

In more recent years, with the growing importance of sustainability, many studies have been published with the aim of including this topic into the BSC. As part of this Dissertation, therefore, a review of the architectures of Sustainability Balanced Scorecards has been conducted [2] [3], showing that there is wide (albeit not unanimous) academic consensus around the usefulness and effectiveness of SBSCs in integrating sustainability into companies' strategies, and allowing to gather the following SBSC architectures (see also Table 1):

- **SBSC-4:** the Sustainability Balanced Scorecard integrates environmental and social measures into the four "traditional" perspectives of the BSC. The SBSC-4 can be designed in two different ways:
  - **Partly integrated**: environmental and/or social indicators are included in some but not all of the four perspectives;
  - **Broadly integrated**: environmental and/or social indicators are included in all four perspectives.
- **SBSC-5+:** the Balanced Scorecard is integrated with one or more non-market perspectives, specific to social and/or environmental measures, increasing the number of perspectives from four to five or more;
- **Extended:** the two architectures previously mentioned are integrated. This means that environmental and/or social measures are spread throughout the four "traditional" perspectives and one or more additional perspectives;
- **Derived environmental and social scorecard:** a new, separated Balanced Scorecard which

only includes social and/or environmental measures is derived from an existing SBSC;

- **Sustainability Evaluation Model (SEM)** or **TBLxBSC**: the four "traditional" perspectives are expanded by considering for each one of them indicators from the three bottom lines of the TBL model (environmental, social and economic), creating a total of 12 correlations.

Where the non-market indicators are added	SBSC-4: Partly integrated	SBSC-4: Broadly integrated	SBSC-5+	Extended	Derived scorecard	TBLxBSC
Additional scorecard					X	
Additional perspective(s)			X	X	(X)	
Additional dimensions in the 4 perspectives						X
All of the 4 perspectives		X		X	(X)	
Some of the 4 perspectives	X				X	
	Sustainability Balanced Scorecard architectures					

Table 11. SBSC archetypes

This paragraph, therefore, lays the groundwork for the introduction of circularity metrics into companies' Balanced Scorecards.

2.2. Circular Economy

2.2.1. Circular Economy Strategies

The literature research conducted in this Paragraph, which led to the analysis of 14 papers, was functional to identifying different frameworks presenting multiple Circular Economy Strategies that can be adopted by companies (see Table 2). Those are:

- **ReSOLVE**: includes Regenerate, Share, Optimise, Loop, Virtualise, Exchange as CE strategies;
- **3R**: includes Reduce, Reuse, and Recycle;
- **4R**: not only the 3R previously mentioned, but also Recover;
- **6R**: in addition to the 4R previously mentioned, Redesign and Remanufacturing are added;
- **10R** [4]: includes Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Repurpose, Remanufacture, Recycle, Recover, and is the most complete framework present in literature.

Strategy	3R	4R	6R	10R	Brief description
Refuse			X	X	Avoid or make redundant a material
Rethink				X	Re-elaborate a product
Reduce	X	X	X	X	Decrease the amount of material
Reuse	X	X	X	X	Use the product more than once
Repair				X	Maintain a product
Refurbish				X	Restore a product to its original function
Remanufacture			X	X	Reuse components in a new product with the same function
Repurpose				X	Reuse components in a new product with a different function
Recycle	X	X	X	X	Reprocess materials to obtain new ones
Recovery		X	X	X	Incineration of materials

Table 22. CE Strategies

2.2.2. Circular Economy Indicators

In this Paragraph, a thorough literature review of Circular Economy metrics was conducted, which led to the selection and analysis of three studies, out of which 152 micro-level, non-industry-specific, strategic CE metrics were extracted. For these metrics, a classification was operated, attributing to each indicator a name, acronym, short description, and the following descriptors (both intrinsic to the indicator and relative to the measuring companies):

- Circularity strategy/strategies measured, on the 10R framework;
- Perspectives of the BSC addressed;
- Type of metric (indicator, framework of indicators, matrix…);
- Minimum circular maturity level at which the indicator can be used (see following Paragraph).

By quantitatively analysing the indicators selected, it is evident that most of the research about Circular Economy indicators is focused around recycling (65% of indicators measure the recycling strategy) and around material flows (which causes 81% of metrics to address the Internal Business Process perspective of the BSC).

2.2.3. Circular Maturity Level

This Paragraph was devoted to understanding how different levels of pervasiveness of the Circular Economy into a company's strategy and operations can be classified into what Nygaard Uhrenholt et al. define circular maturity levels [5]. In the study, they distinguish among the following six levels:

- **Maturity level: none**. No presence of circular awareness nor practices;
- **Maturity level: basic**. Discussions on CE adoption are ongoing, with some limited and unintentional CE practices;
- **Maturity level: explorative**. "Demonstration projects and pilots are initiated across different functions in the organisation" [5];
- **Maturity level: systematic**. CE goes past the pilot stage and is finally integrated into all the company's operations;
- **Maturity level: integrative**. The company integrates its CE practices and strategic focus with its supply chain;
- **Maturity level: regenerative**. The organisation has embraced circularity to the core and "has achieved absolute decoupling of value creation and resource consumption" [5], both of which, therefore, are stand-alone company bottom lines.

2.3. Research opportunities

Thanks to the extensive literature review carried out in the previous Paragraphs, an analysis of the gaps in literature was conducted, leading to the formulation of the two following Research Questions:

1. **RQ1**: *Can including indicators of Circular Economy into a company's Performance Management System support the company's circular transition? And if so, what is a theoretically founded and practically effective way of performing this integration?*
2. **RQ2**: *How can a classification of existing Circular Economy indicators be operated so that it takes into account both characteristics intrinsic to the indicators and characteristics of the companies they are applied to?*

These questions aim to foster a more holistic approach to CE, moving beyond isolated initiatives and embedding CE practices more deeply within organizations.

3. Model Development

Starting from the identified Research Questions, a model facilitating the integration of circularity metrics within the Performance Management Systems (PMS) of companies across various industries, employing different Circular Economy (CE) strategies, and possessing diverse CE maturity levels, was proposed. The Balanced Scorecard (BSC) has been chosen as the PMS for the model due to its flexibility and adaptability, allowing for the inclusion of circularity metrics and innovative architectures, and to its widespread dissemination.

This approach allowed to include within the study the widest possible number of companies (thus supporting the further dissemination of CE), while at the same time leaving space to adapt the model to different, existing BSC (or SBSC) architectures, while keeping the focus of the research on Circular Economy.

In order to create the mentioned model, the following key steps were taken:

1. The review of existing Sustainability Balanced Scorecard architectures conducted in Paragraph 2.1 offered valuable insights into the formulation of Circular Balanced

Scorecards by adapting some of the SBSC architectures identified;

2. Each CBSC architecture was associated to a specific CE maturity level, in order to reflect, for instance, the need of companies with a higher maturity level of a more complex and circularity-focused CBSC. This approach aligns with the one followed by Hansen and Schaltegger [2], who established a hierarchy of SBSC architectures based on the "advancement" level in sustainability practices.

Thus, starting from the studied CBSC archetypes [2] [3] and the existing organizational CE maturity levels [5], the following 5 model architectures (rows) were defined for each type of CE maturity level (columns) (Table 3):

	None	Basic	Explorative	Systematic	Integrative	Regenerative
Traditional BSC	X					
Partly Integrated CBSC-4		X	X			
Broadly Integrated CBSC-4				X		
Extended CBSC					X	
Derived CBSC						X

Table 33: Allocation of CBSC archetypes to different CE maturity levels

Subsequently, each CBSC archetype was populated with the Circular Economy metrics extracted and classified in Paragraph 2.2.2. For this step, two of the descriptors characterizing each indicator were used:

- The BSC perspective that each indicator addresses, in order to correctly assign each indicator inside the CBSC;
- The minimum circularity maturity level, so that indicators that are too advanced for companies in a specific maturity level are not incorrectly attributed.

This phase allowed to draft five models (one for each CE maturity level excluding "none") populated with all the CE indicators that could possibly apply. This means that a selection of indicators based on company-specific characteristics will be performed in the next Chapter.

4. Model validation: empirical study and discussion

The primary objective of the empirical phase is to assess the relevance and utility of the designed theoretical models for companies in various stages of CE adoption, with the goal of enhancing CE integration into corporate strategies. The empirical study involved the selection of 6 companies with diverse CE maturity levels, operating in different sectors and implementing different CE strategies, followed by interviews and meetings with experts and managers within those firms. For each company, a tailored CBSC architecture (considering its CE maturity level) populated with a set of indicators was proposed. In order to select the most suitable indicators for each company, the following two steps were undertaken:

- A first filtering stage considering the industry in which the company operates and the field of activity of each company;
- A second filtering stage leveraging on the 10R framework to select only the CE metrics relevant to the CE strategies the company adopts.

The company-specific models were shown to companies in interviews aimed at gathering feedback on the following questions:

1. "Can the BSC be an effective tool for CE integration in the company's strategy?"
2. "Does the company already measure any of the presented CE indicators?"
3. "Do the presented indicators work for the company and for its CE journey?"
4. "Does the presented structure of the CBSC work for the company and for its CE journey?"

Thanks to the feedback obtained by the interviewed firms, it was possible to draw the following conclusions. Firstly, some interviewed companies acknowledged the CBSC as a valuable tool for visualizing and organizing their KPIs, though none of them used it at the moment of the interview. Secondly, all companies agreed that the identified maturity levels accurately described their CE status. Thirdly, some of the metrics proposed in the model were already measured by the companies, highlighting that the indicators gathered and classified in this Dissertation represent a fairly complete selection. Moreover, most metrics were deemed fitting for the companies' CE journeys, even though some sector-specific metrics were missing. Overall, feedback from the companies was positive: those providing feedback on the CBSC model found it relevant and potentially instrumental in driving CE adoption and dissemination within their organizations. The interviewed companies suggested, as future research possibility, to explore how to integrate current and future legislative requirements into the model and examining its relation to existing CE measurement standards.

5. Conclusions

5.1. Rationale of the work, research approach and conclusions

In conclusion, it is possible to give an answer to the two Research Questions. Regarding RQ1, the positive feedback given by the interviewed companies demonstrates how the use of the CBSCs can help companies integrate the CE into their corporate strategies and foster the implementation of CE practices. Concerning RQ2, the Literature Review was essential in gathering indicators, on which a classification was operated, based on both characteristics intrinsic to the indicators (e.g., type of metric) and characteristics related to the company using the indicator (e.g., CE maturity level). 4

5.2. Theoretical implications

The key contributions of this Dissertation to research are the following. Firstly, a thorough examination of existing studies on CE indicators was conducted, resulting in the creation of an orderly and comprehensive list of classified CE metrics. Secondly, the work demonstrates that integrating CE metrics into PMSs using the CBSC is a viable approach for companies aiming to incorporate CE into their strategies. Thirdly, the validation phase yielded positive results, confirming the relevance of the list of CE indicators in this work for advancing CE in companies.

5.3. Managerial implications

This study offers a valuable methodology to enhance managerial practices: firstly, the identification of the CE maturity level helps companies understand their current position in terms of CE adoption, highlighting existing practices, and outlining necessary steps to progress towards higher CE maturity levels; secondly, companies are provided with a curated list of CE indicators, systematically classified for easy selection; thirdly, the model offers managers a comprehensive understanding of the CE, visually representing its multiple dimensions and offering a practical and integrated approach to link CE indicators with more familiar financial and operational metrics; finally, the model guides and supports companies in integrating the circular economy into their existing PMS and, consequently, into their corporate strategy.

6. Acknowledgements

Special thanks go to Professor Davide Chiaroni and to co-advisor Laura Marcati for their support during these intense last few months. We are thankful to all the company representatives that contributed to this work and to our families and friends who stood by us throughout this journey.

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MILANO 1863

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Abstract

The concept of Circular Economy (CE) has received significant attention in recent years, yet a structured and comprehensive approach to CE measurement and its integration into corporate strategy is yet to be elaborated, relegating CE to isolated initiatives.

This dissertation addresses this gap through a literature review focused on the Balanced Scorecard (BSC) and Circular Economy, and then elaborating research questions aimed at exploring the integration of CE indicators into Performance Management Systems and classifying existing CE indicators based on their characteristics and applicability. The Model Development section builds upon the traditional BSC framework and on Sustainability BSCs to create Circularity Balanced Scorecard (CBSC) archetypes, tailored to different CE maturity levels, subsequently populated with CE indicators. The theoretical model is validated with six companies, whose feedback indicates positive reception, with a significant portion of indicators proposed deemed relevant for their circularity journey. The CBSC architecture is also well-received, demonstrating its potential to drive CE integration in company strategy.

Keywords: circular economy, strategy, balanced scorecard, indicators, circular maturity level

Abstract in italiano

Il concetto di Economia Circolare (CE) ha ricevuto un'attenzione significativa negli ultimi anni, tuttavia non è ancora stato elaborato un approccio strutturato e completo alla misurazione della CE e alla sua integrazione nella strategia aziendale, relegando la CE a iniziative isolate.

Questa tesi affronta questa lacuna attraverso una revisione della letteratura incentrata sulla Balanced Scorecard (BSC) e sull'Economia Circolare, per poi elaborare domande di ricerca volte a esplorare l'integrazione degli indicatori di CE nei Performance Management System e a classificare gli indicatori di CE esistenti in base alle loro caratteristiche e applicabilità. La sezione di Model Development si basa sulla BSC tradizionale e sulle Sustainability BSC per creare archetipi di Circularity Balanced Scorecard (CBSC), adattati a diversi livelli di maturità della CE e successivamente popolati con indicatori CE. Il modello teorico è stato validato con sei aziende, il cui feedback indica un'accoglienza positiva, con una porzione significativa di indicatori proposti ritenuti rilevanti per il loro percorso di circolarità. Anche l'architettura CBSC è stata accolta positivamente, dimostrando il suo potenziale nel contribuire all'integrazione della CE nella strategia aziendale.

Parole chiave: economia circolare, strategia, balanced scorecard, indicatori, livello di maturità circolare

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1 Introduction

1.1. Sustainable Development

At the time of writing of this introduction, the World is experiencing its warmest month in recorded history, with global surface air average temperatures nearing 17°C [1]. This is not an isolated event: anthropogenic climate change is a phenomenon that is now acknowledged by more than 99% of peer-reviewed papers in literature [2]. Its devastating impacts are already visible on the planet: glacier loss, sea level rise, ocean warming, intense heat waves, increased drought, hunger, poor nutrition, increased health risks, poverty and displacement are only some of the effects that climate change is having on the environment and human beings [3]. In order to tackle these issues and prevent new ones, it is important to understand their common cause.

In 1987, the World Commission on Environment and Development (WCED) published the report "Our Common Future" also known as "Brundtland Report" [4], which presents guiding principles for sustainable development. In this document, the fast growth and development that many countries had undergone over the past decades was recognised to having contributed to the worsening of global environmental and social issues. As a matter of facts, on the one hand, there had been a rise in the number of produced goods, which greatly contributed to the generation of pollution for production, usage, and disposal; on the other hand, many products were raw material- and energy-intensive. For instance, fossil fuel usage had increased by over thirty times in the century before the publication of the report, becoming one of the main contributors to climate change. This situation was further worsened by the cutting and burning of forests, which act as sinks of CO_2, and by the evolving patterns of consumption and decision making: on the one hand, consumption mainly happened in the so-called "developed" countries, which at that time were also more mature and growing at a slower pace, while "developing" countries made up for a minority of world consumption of many goods and services, despite growing at a faster pace; on the other hand, governance was still in the hands of nation states, while environmental matters transcend political borders and require a collective decision-making process. All of these characteristics, intrinsic to the development path the World had in 1987 and, in most cases, to the current development path, led the World Commission on Environment and Development to define Sustainable Development as the

"development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

This definition outlines two key elements of Sustainable Development: firstly, it is based on the notion of "needs", highlighting the undesirability of the current situation of deep intra-generational inequality, with a share of the world unable to meet its basic needs and another living above planetary means; secondly, it focuses on inter-generational equality and on avoiding burden shifting on future generations.

The report also presents seven “Strategic imperatives”, strategies that, according to the proponents, would allow to transition from a destructive development path to a sustainable one. In particular, the fifth of these seven imperatives recognises that the resources in the world are finite and thus revolves around the concept of conserving and enhancing the resource base. It becomes apparent, therefore, how tightly intertwined sustainable development is with a more attentive management of natural resources, be it material or energy resources: a concept that would stay relevant in the decades to come, thanks to the development of an innovative economic paradigm: that of Circular Economy.

1.2. The circular economy paradigm

As stated in the Brundtland Report, “Nature is bountiful, but it is also fragile and finely balanced. There are thresholds that cannot be crossed without endangering the basic integrity of the system”. One of these limits is resource availability. Indeed, there are two types of sources: *renewable resources*, which can naturally replenish themselves, and *non-renewable resources*, that are instead limited in supply [5]. The issue of resource scarcity concerns the latter, such as fossil fuels (oil, natural gas, coal) and minerals, since a fast economic growth that makes use of non-renewables will contribute to the decrease of their availability in nature. However, today, human society mainly relies on fossil fuels as its primary source of energy and has yet to abandon or significantly reduce its dependence on minerals extraction.

The issue of resource scarcity was already clear in 1798, when Thomas Malthus wrote about the future supply incapacity of farmlands due to the increase in demand following a growth trend in the population [6]. Subsequently, in 1865, William Stanley Jevons published a work in which he raised concerns about the scarcity of coal due to the increasing extraction rates [7]. In addition to this, in 1972, the report The Limits to Growth studied the change in the finite supply of resources in relation to exponential economic and population growth [8]. Despite all this evidence, the current economic paradigm is not yet able to respect planetary boundaries and, every year, the Earth Overshoot Day (EOD) falls earlier and earlier. This indicator is computed taking into consideration the amount of resources generated by the Earth in the reference year, namely planet's biocapacity, and human's demand of resources for that year, namely humans' ecological footprint [9]. It is clear that without a change in the current economic model, the Earth's biocapacity will not be able to replace the used resources with new ones. This is why the paradigm of the Circular Economy has gained momentum over the past years: it is a way to enable companies to shift from the Take-Make-Dispose model, which is no more sustainable both from an economic and from an environmental viewpoints, to a more attractive alternative (as shown in Figure 1).

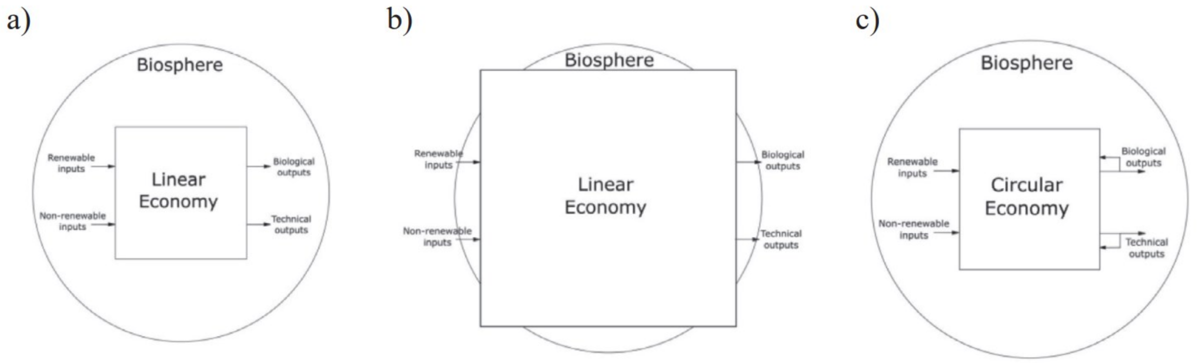

Figure 1 [10]. Relationship between the economic system and the biosphere. Linear economy system was feasible in the past (a). Currently, the linear economic system's size is bigger than the biosphere's size in terms of consumption and extraction rates (b). Circular economy aims to adjust these rates to planetary boundaries again (c).

One single and shared definition of Circular Economy does not exist [11]. However, the Ellen MacArthur Foundation (EMF), a pioneer in this field, well describes the three principles that lie behind it.

- The first pillar is to "*design out waste and pollution*", which involves creating products and processes that generate minimal waste and pollution throughout their entire lifecycle. Right now, once a product reaches its End-of-Life (EoL) it usually ends up in landfills or incinerators and it is lost. Through the implementation of circular business models, the product and/or its materials re-enter the economy and are re-worked. In this sense, the design phase of every good or service is crucial: by optimizing the structure of the final product and of its components, and by carefully choosing the right materials, it is possible to reduce the amount of waste and pollution generated by the product throughout its whole life cycle [12];

- The second pillar is to "*circulate products and materials*", which emphasizes the importance of creating loops to keep products and materials in use as long as possible to prevent them from becoming waste and to retain their intrinsic value within the economy. This principle aims to reduce the need for virgin feedstock too and involves many circular practices, which are identified by the Butterfly Diagram (Figure 2). These practices can be divided into two groups: the *technical cycle* and the *biological cycle*. The former includes all those flows that enable companies to keep their products and materials in circulation; the latter explains how the nutrients of biodegradable materials are returned to the Earth to regenerate nature [13];

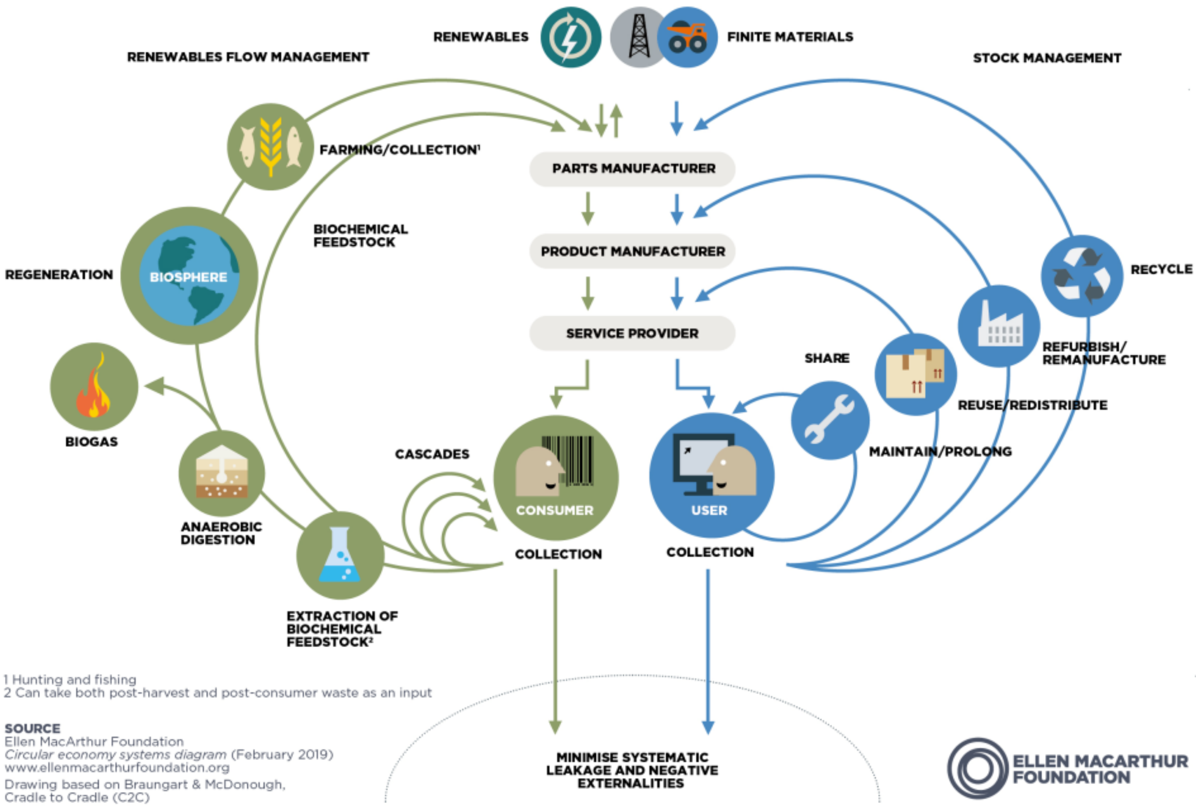

Figure 2 [14]. The Butterfly Diagram

- Lastly, the third pillar: "*regenerate nature*". This principle focuses on restoring and regenerating natural ecosystems, which are important for preserving the health of the planet. It involves shifting from the extraction of raw materials to the regeneration of the natural capital, designing systems that respect nature and prioritize the conservation and restoration of biodiversity [15].

As a consequence of its characteristics, the Circular Economy is especially important in decoupling economic growth from resource consumption and its negative impacts [16] (Figure 3). More specifically, *resource decoupling* aims to increase resource use efficiency by "using less material, energy, water and land resources for the same economic output". It is particularly important when a resource is in short supply or when it has severe environmental impacts, making it imperative to reduce its use in production. *Impact decoupling*, instead, focuses on "increasing the economic output while reducing negative environmental impacts", which are caused by resource extraction, production, commodity use phase and End-of-Life treatment. When a resource's environmental impact threatens ecosystems and human health, or when there are technologies that can lessen this impact, this type of decoupling is crucial. Once they have been defined, the two types of decoupling can be classified as *absolute decoupling* or *relative decoupling*. In the first case, when the economic driver increases in value, the use of resources declines in absolute terms. In the second case, instead, there is a positive relationship between the growth rates of the economic driver and of the resource use (or the environmental impact), but the former is lower than the latter.

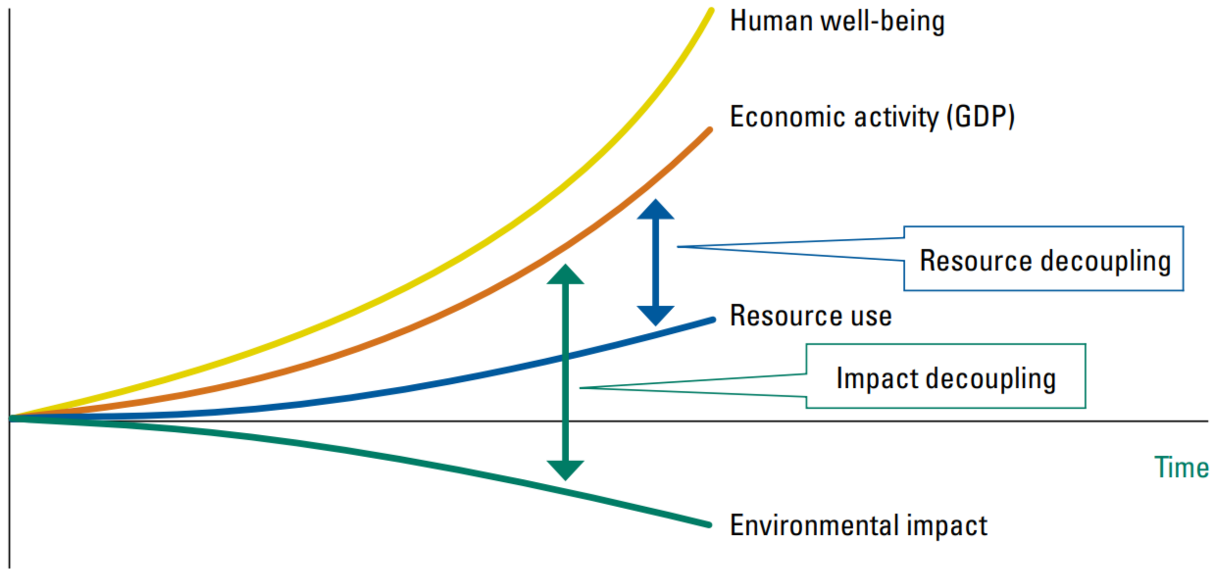

Figure 3 [16]. Resource and impact decoupling

1.2.1. Circular economy principles

A circular economy can take advantage of four virtuous properties of looping, which are patterns for creating value from the materials used in consumer goods [17] (Figure 4). Although the implementation of the Circular Economy strategies is sector-specific, these four principles endure in any sectors:

- "*Power of the inner circle*": the closer the strategy gets to direct reuse, the more valuable it is. As an example, savings in terms of material, labour, energy and money increase when shifting from the "Recycle" strategy (outer circle) to the "Reuse" one (inner circle), therefore the associated negative environmental externalities and economic impacts are lower. As a matter of facts, by implementing inner circles of the Butterfly Diagram, there will be a reduction in the use of virgin materials and in the number of operations needed, besides a better End-of-Life management, since the product and/or its materials will be looped back into the system and reworked by the company, avoiding all the potentially energy-intensive steps of the upstream supply chain and the disposal phase.

- "*Power of circling longer*": value is created by extending the useful life of products, parts, and materials. This can be achieved in two ways: either by allowing for a higher number of consecutive circles (consecutive lifecycles of products, parts and materials) or by spending more time in a single circle. As the previous principle, the "power of circling longer" avoids material, energy, and labour costs. However, it is important to highlight two aspects: the first one is that operating, maintenance and opportunity costs will rise, and the second one is that for products requiring energy, the evolution of energy performance over time must be considered, particularly during the usage phase: sometimes an outdated product is less efficient than purchasing a new one.
- "*Power of cascaded use and inbound material/product substitution*": using discarded materials from one value chain replacing virgin materials in another. The costs coming from repurposing the by-products of one industry, as well as the negative environmental externalities, may be lower than the ones that would be generated using raw materials.

- "*Power of pure, non-toxic, or at least easier-to-separate inputs and designs*": mixtures of materials caused by design choices or by wrong waste collection management prevent companies from preserving the purity and quality of materials. It is important that the product can be separated into its original components and that different materials can be separated in different streams. To do so, the product's End-of-Life must be anticipated during the design phase, through reasoned choices in terms of materials and structure of the good.

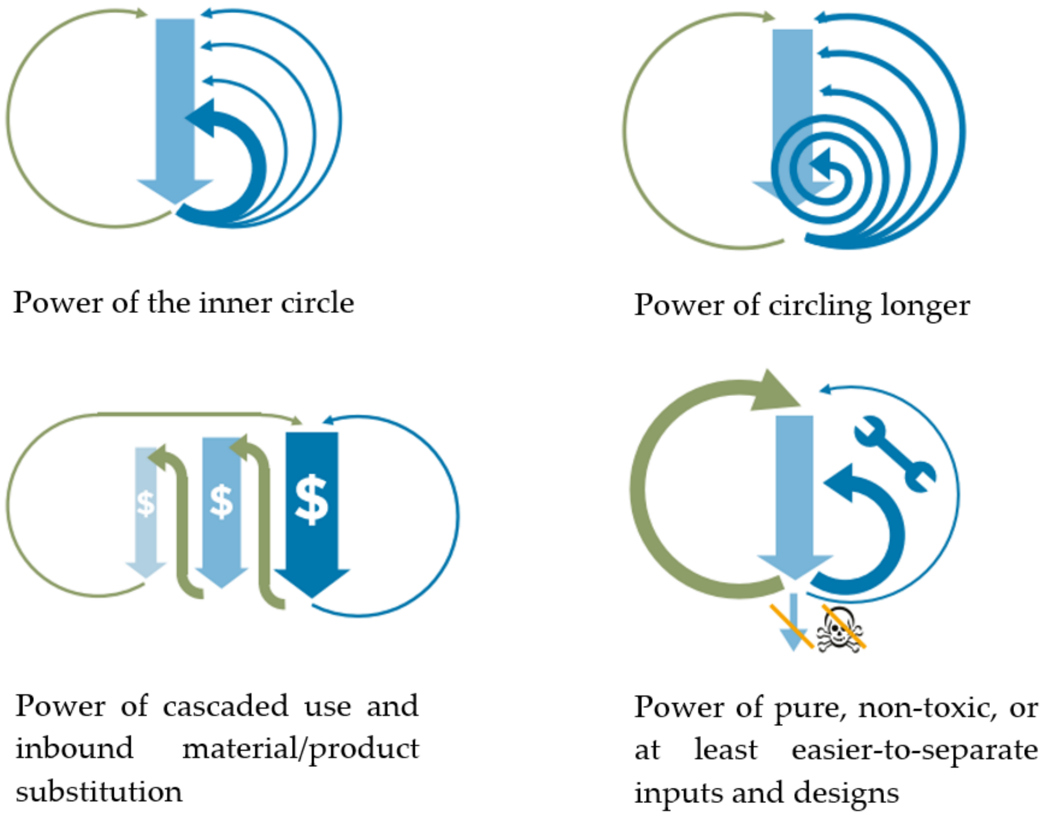

Figure 4 [17]. CE principles

1.2.2. CE and Sustainability

Sometimes the two concepts of Circular Economy and Sustainability overlap and are erroneously used in the place of one another. However, despite having some similarities, they also display differences [18]. They will both be tackled in this paragraph.

Firstly, the similarities are going to be highlighted. Both concepts are based on the importance of intra- and inter-generational commitments motivated by environmental risk, meaning that the current population should be able to meet its needs, while securing to the future generations the possibility to meet their own. This should be accomplished by making use of technologies that are already in place as well as new technological innovations, looking for synergies between them. Additionally, both Sustainable Development and CE have a global outlook that emphasizes the necessity of cooperation between numerous actors who have shared responsibilities. To align stakeholders, they rely on regulations and incentives which aim at standardizing the implementation process of the two concepts and hastening the shift towards a more circular and a more sustainable economic model. Moreover, they are multi-perspective concepts that do not just emphasize the economic viewpoint. To make all these perspectives synergetic, they propose system changes and business model innovations. Finally, both Circular Economy and Sustainable Development result from interdisciplinary research fields and have private businesses at the core, due to their know-how and resources.

Secondly, the two concepts also display differences. For instance, the concept of CE is more recent than the one of Sustainable Development. Moreover, the two have different objectives: CE's goals are well defined, namely closing the loop of material flows to reduce the virgin material inputs and the waste generation, while also generating profit; Sustainable Development's objective, instead, is broader and adaptable to the context since it refers to a type of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In addition, the main stakeholders are different: in the case of the CE, the beneficiaries are primarily the environment and the economic actors involved in the implementation of circular business models, leaving social aspects only marginally covered, constraining them to job creation. Sustainable Development, instead, positively impacts all the three pillars of the Triple Bottom Line: the environment, society and the economy. Another difference lies in the time dimension that the two concepts have for achieving their objectives: Sustainable Development's one is open-ended (goals are adapted over time) while CE's one is limited due to biological and technical constraints. Finally, the concept of responsibility is declined differently: in the case of Sustainable Development, responsibilities are shared between multiple actors, but none of them has a clearly defined role, whereas when it comes to the Circular Economy, the main responsible players are private businesses concerned with the implementation of new business models, as well as regulators and policy makers who act as drivers or barriers for the shift from a linear to a circular economic model.

The concept of Sustainable Development can be summarised using the 17 Sustainable Development Goals outlined by the United Nations in the 2015 "Transforming our World: The 2030 Agenda for Sustainable Development" report [19]. They address all three aspects of the Triple Bottom Line and are broken down into 169 targets that are meant to accomplish the aforementioned goals. Numerous studies have attempted to establish a connection between the CE and the SDGs, and, despite the fact that their conclusions can occasionally differ slightly, these studies are significant because they demonstrate how, whether directly or indirectly, the CE helps pursue many of the 17 SDGs. For instance, as shown in Figure 5, the Ellen MacArthur Foundation claims that the Circular Economy helps achieve the SDGs [20] highlighted in Figure 5.

Figure 5 [20]. SDGs impacted by the CE according to the Ellen MacArthur Foundation

In addition, P. Schroeder, K. Anggraeni, and U. Weber suggest an alternative list of SDGs impacted by the CE [21]. They distinguish between goals that are directly impacted and those that are only indirectly affected: among the ones with strong links and synergies, one of the most impacted goals is the SDG12 (Sustainable Consumption and Production), due to the intrinsic nature of the CE, together with SDG6 (Clean

Water and Sanitation), SDG7 (Affordable and Clean Energy), SDG8 (Decent Work and Economic Growth) and SDG15 (Life on Land); an indirect influence concerns SDG1 (No Poverty), SDG2 (Zero Hunger) and SDG14 (Life Below Water). However, there are 35 targets that show weak or no links with CE, that belong to SDG3 (Good Health and Well-being), SDG5 (Gender Equality), SDG 10 (Reduced Inequalities), SDG11 (Sustainable Cities and Communities) and SDG16 (Peace, Justice and Strong Institutions). All these observations show how the CE is strictly connected to the Economic and the Environmental pillars of the Triple Bottom Line, but it is still weak in terms of impacts on Social sustainability.

Nowadays, it is crucial for every company to have a structured performance measurement system that can serve both external and internal uses [22]. The disclosure of KPIs (Key Performance Indicators) to external parties is known as *external accountability*. The actors interested in these indicators are external stakeholders, which include shareholders, debtholders and other societal actors that are impacted by the company's economic, social, and environmental performance, as well as the risks associated with the firm's operations. For example, shareholders, who serve as the organization's primary risk-capital investors, are interested in maximizing company value and assessing how the company is performing; debtholders want to know the firm's level of security before approving loans; other stakeholders, including local communities, suppliers, and customers, are concerned with the company's reputation, governance, and effects on society and the environment. Stakeholders can get insights into all these aspects by using the external reporting documents published by the company. *Internal accountability*, on the other hand, refers to the disclosure and use of performance indicators to and by internal stakeholders, including the functional units and managers of the company. They use KPIs in the decision-making process to set goals, define whether they are coherent with the overall organizational strategy, monitor company's performance and benchmark it both over time and against other actors of the industry, thus making internal accountability a powerful and irreplaceable instrument in the management of companies and organisations.

Nonetheless, despite the great relevance that the concept of Circular Economy has come to have in recent years, and despite the huge importance of measurement in corporate governance, a structured and comprehensive approach to micro-level CE measurement has yet to be developed and agreed on. Many studies have outlined this gap in knowledge [23], which prevents companies and organisations from having a strategic understanding of Circular Economy, which, instead, stays limited to isolated initiatives.

1.3. Structure of the Dissertation

This Dissertation is focused on expanding on the existing knowledge on the Circular Economy by tackling the research gaps mentioned in the previous paragraph and that will be examined in more depth at the end of the next chapter. The structure adopted in this Dissertation, therefore, begins necessarily with a Literature Review, aimed at gaining a better understanding of the existing literature on two central topics of this work:

- The **Balanced Scorecard**: this section focuses on presenting the structure of the traditional Balanced Scorecard, as described by Kaplan and Norton, the creators of this Performance Management System, and subsequently on researching on the ways the BSC has been adapted and expanded to integrate Sustainability indicators and, therefore, to make Sustainability a key strategic focus for companies and organisations;
- The **Circular Economy**. This part of the Literature Review focuses on the following topics:
    - **Circular Economy Strategies**: CE strategies enable companies to implement and pursue the Circular Economy. Several strategies exist, which are more or less implemented by firms, therefore, it is necessary to find frameworks and models that identify and list them in a clear and complete way.
    - **Circular Maturity Levels**: companies that implement circular practices within their business models do not necessarily have the same level of CE maturity. Indeed, the implementation of the Circular Economy can be restrained to specific areas or be pervasive to all organisational functions, based on the firm considered. Therefore, it is important to find

a model that is able to identify and list possible company's CE maturity levels.

- **Circular Economy Indicators**: it is crucial for companies that implement the Circular Economy to measure their performance in order to raise awareness on their state of the art, and to understand their objectives and how to pursue them.

Towards the end of the Literature review, after gaining better understanding of the current state of research in both of these key topics, a paragraph on Research Opportunities is going to be compiled, highlighting the key gaps in knowledge and the research questions of the Dissertation.

Subsequently, the Model Development chapter will be used to theoretically assemble a range of different models to integrate Circular Economy metrics into companies' and organisations' Performance Management Systems, through multiple steps:

- Firstly, a paragraph defining the area of applicability of the model is going to set the scope of the model development in terms of sector specificity and of interaction with sustainability;
- Secondly, Circularity Balanced Scorecard architectures, based on the literature analysed on the BSC and on the circular maturity level, will be formulated

- Lastly, a number of Circularity Balanced Scorecard models, integrating the CE metrics identified in the literature review in the CBSC architectures, will be elaborated.

After the definition of the models, they are going to be tested in order to understand whether or not they have the right structure and the right scope of application. This will be done in the paragraph "Model Validation: Empirical Study". In order to carry out the empirical analysis, a number of companies will be selected, then the created models will be customised based on the company CE maturity level, the CE strategies it implements, and on its sector of operation and, finally, they will be submitted and presented to the companies through an interview. The paragraph is made of two parts:

- In the "Interview Building" paragraph, the way in which the models are customised is presented;
- In the "Interviews" paragraph, a description of the customised models and of the company's feedback will be reported for each interviewed organisation. A few indicators are selected from the original model based on the characteristics of the considered company: only those metrics judged most suitable will become part of the interview. The comments and feedback on the models coming from the interviewed companies will be reported too.
- In the "Empirical analysis conclusions" paragraph, the feedback given by the interviewed companies will be presented and summarised.

The last paragraph, “Conclusions”, includes a final analysis and some considerations concerning the proposed models and the feedback received during the empirical study.

2 Literature Review

2.1. Balanced Scorecard

2.1.1. Research Papers Selection

As seen in the previous chapter, performance measurement is essential in every organisation, especially when considering more complex entities. Nevertheless, performance measurement is no easy task and can be done in countless different ways: therefore, numerous attempts at standardisation have been made. It is apparent that the most successful of these attempts is the Balanced Scorecard (BSC), which, as outlined in the introduction, is still to this day the most-widely adopted PMS and the one that generates the most interest in the scholarly community.

Therefore, for the purpose of this paragraph a literature review for sustainability and circularity applications of the BSC has been carried out, in order to have a solid theoretical grounding with the aim of proceeding with the design of a scorecard which includes circularity performance measurement. The aim of the research was to find information about sustainability and circularity Balanced Scorecard designs and architectures, understanding the advantages and disadvantages of each architecture and of the general concept, while excluding case-specific applications. In order to achieve this goal, the material collection was carried out through the database Scopus, with the following research criterion:

TITLE-ABS-KEY ("balanced scorecard" AND (circular OR circularity) OR (sustainable OR sustainability)) AND (LIMIT-TO (SUBJAREA , "BUSI"))

This led to the identification of 266 papers within the subject area of "Business, Management and Accounting" related to circular or sustainable balanced scorecards. Subsequently, two screening phases were conducted. The first one was executed with a focus on the titles of the collected papers and led to the exclusion of a total of 233 papers, either because they were too distant from the topic of interest or too inclined towards case-specific analyses that did not align with the broader objectives of the research. The second step was based on the analysis of the abstracts or of the entire text of the remaining 33 papers. This evaluation led to the exclusion of further 18 papers, either because they were case- or application-specific, they did not focus on Sustainability BSC or because they offered restricted access. This led to the final selection of 15 papers which were judged suitable for the research purposes, 7 of which were literature reviews and 8 were not, allowing for a complete overview of existing literature on the topic. At the same time, three additional papers were included in the analysis, in order to give a solid background on the structure and functioning of the BSC.

2.1.2. Introduction to the Balanced Scorecard

The Balanced Scorecard was first proposed in 1992 in a Harvard Business Review article by Robert S. Kaplan and David P. Norton [24], who later in two 1996 papers coined the basic elements of the structure of the BSC [25] [26]. The foundational premise on which the Balanced Scorecard is based is that neither financial measures nor operational measures alone are enough to have a good picture of the performance of a company: financial measures are usually less innovation-oriented and stakeholder-oriented, while operational indicators alone cannot completely describe the value created by an organisation. This is why the Balanced Scorecard is divided into four perspectives (Figure 7), each of which is described with a number of indicators and a question it tries to give an answer to. Those are the financial perspective ("How do we look to shareholders?"), the customers perspective ("How do customers see us?"), the internal business perspective ("What must we excel at?"), and finally the learning and growth perspective ("Can we continue to improve and create value?").

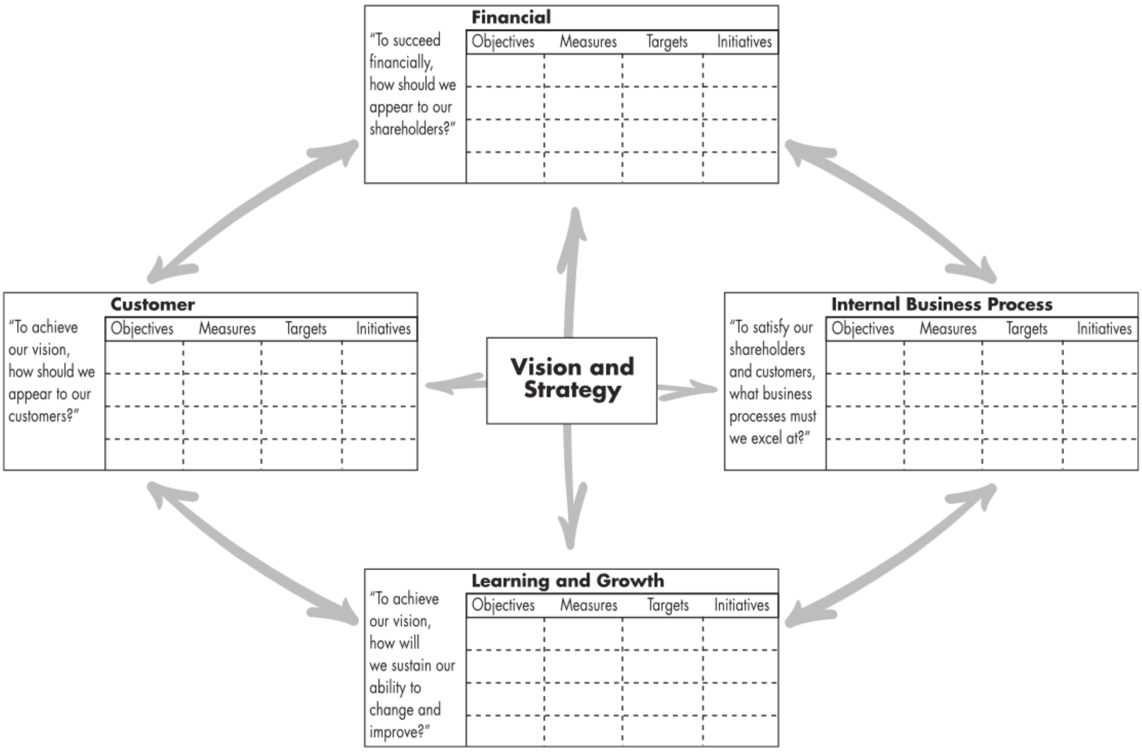

Figure 6 [25]. The four perspectives of the Balanced Scorecard

Kaplan and Norton suggest four to seven indicators to be included in each perspective, balancing leading indicators (the ones that measure immediate change and progress) and lagging indicators (the ones that measure the outcomes of changes and progress made). These may seem like a lot, but according to Kaplan and Norton these different and often divergent indicators all stem from the same company strategy, thus each of them conveys and explains a different aspect of the same, unified strategy: it is therefore key, in the opinion of Kaplan and Norton, to design a fitting company strategy and to ground the BSC to a strategy map, outlining clear cause-effect linkages among indicators, in order to make the scorecard cohesive and guide decision-making. However, other authors have expressed scepticism on strictly causal structure and proposed other, looser structures. In particular, Hansen and Schaltegger [27] grouped those alternative proposals into three categories: "Strictly hierarchical" (as proposed by Kaplan and Norton, all the indicators are strictly connected to one or a handful of indicators and factors, often financial, to be maximised, representing the ultimate strategic goal of the company), "Semi-hierarchical" (the cause-effect linkages among indicators are loosened, giving more space for complex interdependencies and for more than one bottom line), "Non-hierarchical" or "Network" (causal linkages are non-existent, leaving space for complex, multi-objective and multi-stakeholder management practices, possibly at the cost of losing focus); the choice of one of the three mostly depends on the company's value system, that is, the degree of focus it places on the financial bottom-line.

It is therefore clear that the BSC is not just useful for measuring performance, but also for a much wider range of objectives, such as (quoting from [25])

- clarify and update strategy internally;
- communicate strategy throughout the company;
- align unit and individual goals with the strategy;
- link strategic objectives to long-term targets and annual budgets;
- identify and align strategic initiatives;
- conduct periodic performance reviews to learn about and improve strategy.

All of this partly explains why the BSC has been so successful over the past three decades: at its peak in 2008, 53% of companies had adopted a form of BSC [28], and, despite that rate having fallen to 29% in 2017 [29], the BSC is still generating much greater interest among scholars compared to its alternatives [30], thanks to its clear, flexible and theoretically-grounded structure [31], which makes it suitable for a wide range of applications. This means that among Performance Management Systems the BSC has the prominence and flexibility to be the right instrument for, among others, circularity performance measurement. At the same time, critics have highlighted that the flexibility that characterises the BSC also means that real-world applications of this performance management system have varied widely, becoming a synonym for virtually any kind of scorecard, in many cases decreasing its effectiveness [30]: this does not have to be an obstacle in sustainability- and circularity-related applications of the BSC, but can be seen as an incentive to a rigorous and attentive design.

Since the introduction of the BSC in 1992 a lot has changed in the business environment, including greater attention to the core topics seen in the previous chapter, such as environmental and social sustainability and circular economy, and the ways through which companies can introduce these concepts in their own operations and strategy. The Balanced Scorecard has proven to be one of the most interesting instruments for this purpose among Performance Management Systems: Sustainability Balanced Scorecards have gathered a good number of scholarly publications, for the following reasons (well highlighted in Mio et al., 2021 [32]):

- Many environmental and social issues are non-financial;
- the environmental and social effects of organisational actions mostly manifest themselves over the long term;
- the cause-and-effect relationships that should be hypothesised to develop the BSC may help managers to clarify the connections between long-term resources and capabilities, including sustainability issues and short-term financial outcomes;
- the multi-dimensional approach would allow managers to address environmental, social and governance (ESG) goals whereas other approaches only focus on, for example, the environment;
- sustainability involves a performance measurement system including both leading and lagging indicators.

2.1.3. Literature State of the Art

The research was aimed at gaining a deeper understanding of sustainability Balanced Scorecards in order to lay out a theoretical foundation for the design of a BSC which includes circularity measures.

This is why it is key, as a first step, to identify how wide the consensus around Sustainability Balanced Scorecards is and what the criticisms, if any, are, so that they can be taken into consideration when developing a circularity BSC; subsequently, a review of SBSC architecture is going to be carried out.

Among the 15 studies considered in the research, only one [33] was openly sceptical of the concept of SBSC, while all the others agree at least in principle (and most often in practice) with the efficacy of this instrument. In particular, Hahn and Figge criticize the 2014 study by Hansen and Schaltegger with two main arguments: (i) that the BSC is a misfit to adequately address corporate sustainability and achieve transformational change, and (ii) that this misfit holds regardless of SBSC architecture. Regarding (i), Hahn and Figge develop their criticism along three lines as follows:

- The BSC is only designed to address outcomes (positive or negative) at organizational scale, not at societal scale. While for the financial or customer perspectives this makes sense, social and (even more so) environmental impacts have a much more important global component;
- One of the BSC's distinctive features is the cause-effect map of indicators. This is much harder to be applied effectively for environmental indicators, as their causal linkages are often complex, nonlinear and/or still being researched: this creates the risk of turning a blind eye to those indicators and impacts that cannot be easily aligned to the dominant economic logic;
- The strategy lying behind BSC is hardly going to be reformulated for the SBSC (widening the perspective from a narrow shareholder focus to a multi-stakeholder focus and taking into consideration the heterogeneous and competing logics typical of sustainability-focused organisations), thus

leading to the possibility of justification and reinforcement of current unsustainable business practices.

A response to these criticisms was proposed by Hansen and Schaltegger in a 2018 study [34], which rebuts Hahn and Figge's theses. A number of arguments are made in the study, but a selection of the most relevant for the scope of this research was operated. In particular, Hansen and Schaltegger argue that (i) the SBSC does not need to be an agent of radical change in order to be effective enough to improve the status quo, and thus that (ii) addressing outcomes at an organisational scale instead of a global scale allows to measure the organisation's contribution to the global sustainability outcomes and thus better the current impacts; regarding cause-effect relationships among indicators, Hansen and Schaltegger make the case that (iii) they do not necessarily have to reflect the full complexity of natural systems, as the BSC is a way to manifest the company's strategic understanding of the relationships among its indicators, and not to portray their entire complexity; moreover, (iv) architecture is indeed relevant in this respect, as it allows to reduce (or even annul) the importance of cause-effect linkages among indicators, thus removing the problem altogether.

It can be concluded, therefore, that a wide consensus on the usefulness and effectiveness of the SBSC is shared among scholars. At the same time, it is also important to have an understanding of criticisms made to it, in order to have a more comprehensive theoretical grounding while including circularity in BSC. For this same purpose, as a second step the architectures of SBSCs presented in literature are identified and described.

One of the most complete literature review papers identified through this research is the 2016 study by Hansen and Schaltegger [27], which groups architectures as follows:

- **SBSC-4:** the Sustainability Balanced Scorecard keeps the four "traditional" perspectives of the BSC and integrates environmental and social measures into these perspectives. This allows sustainability performance to be better integrated into the existing business and strategy of the company, but at the same time there is the possibility for this architecture to be less transformational and long-term oriented, as it has to align to current objectives and strategic structure. SBSC-4, according to Hansen and Schaltegger, can be designed in the two following ways:
  - **Partly integrated**: environmental and/or social indicators are included in some but not all of the four perspectives;
  - **Broadly integrated**: environmental and/or social indicators are included in all four perspectives.
- **SBSC-5+** (or Responsive Business Scorecard [35]): the Balanced Scorecard is integrated with one or more non-market perspectives, specific to social and/or environmental measures, increasing the number of perspectives from four to five or more. This allows for a dedicated view of sustainability

indicators without the pressure for a strict financial linkage, even though this comes at a risk that the new perspectives might be loosely or not at all integrated by causal connections with the "traditional" four; some scholars [36] propose that non-market perspectives be used only if the additional environmental/social measures have strategic relevance and at the same time it is not possible to include them appropriately into the four "traditional" perspectives. Additional perspectives could be, for example, a "non-market" perspective (in the case of SBSC-5) [36], a social perspective and an environmental perspective (in the case of SBSC-6) [37], or social, environmental and cost perspectives (in the case of SBSC-7) [38];

- **Extended:** the two architectures previously mentioned are integrated. This means that environmental and/or social measures are spread throughout the four "traditional" perspectives and one or more additional perspectives. Hansen and Schaltegger in their 2016 study describe this architecture as the most progressive, as it allows to combine long-term orientation of sustainability performance measurement and integration within the existing strategic structure, thus creating an advanced sustainability strategic structure suitable even for the most mature organisations in terms of embedding of sustainability in strategy.

Additionally, other architectures not described by Hansen and Schaltegger were identified in literature. These are:

- **Derived environmental and social scorecard** [36]**:** a new, separated Balanced Scorecard which only includes social and/or environmental measures is derived from an existing SBSC (designed utilising one of the previously described architectures). According to Figge et al., this separated BSC is not an alternative to other SBSC architectures, but allows to complement the ones previously described by allowing coordinated control over all the social and environmental measures, giving the possibility to highlight the relationships among the non-market measures and the link to the company's environmental and/or social strategy;
- **Sustainability Evaluation Model (SEM)** or **TBLxBSC** [39]: instead of expanding the number of perspectives of the BSC, the SEM expands the four "traditional" perspectives by considering for each one of them indicators from the three bottom lines of the TBL model (environmental, social and economic), creating a total of 12 correlations (Figure 8).

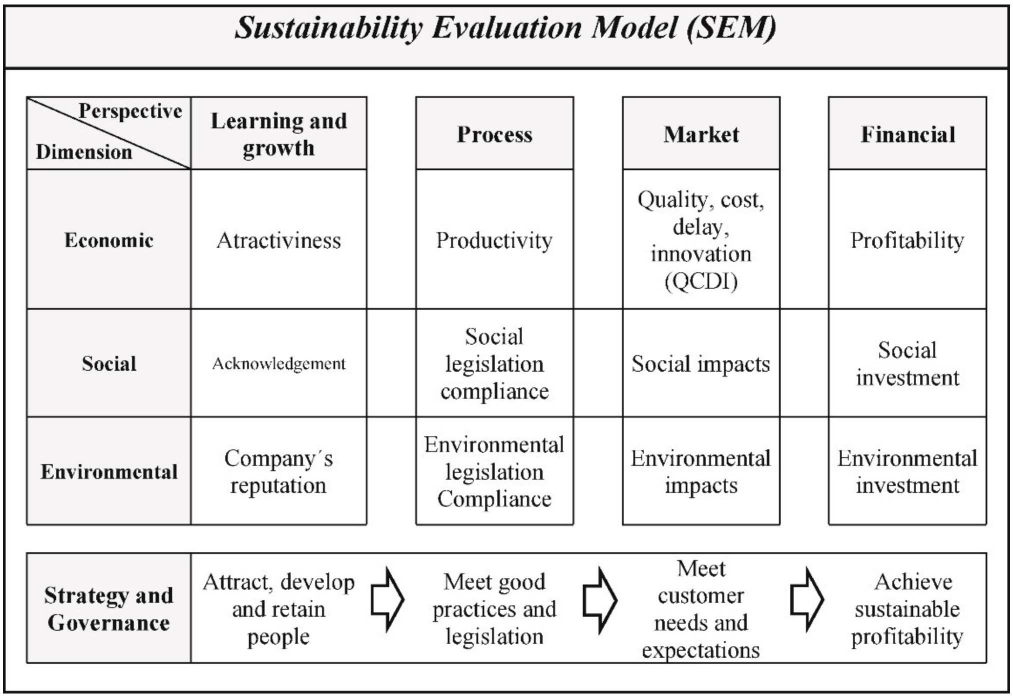

Figure 7 [39]. BSCxTBL model

Where the non-market indicators are added	Sustainability Balanced Scorecard architectures: SBSC-4, Partly integrated	SBSC-4, Broadly integrated	SBSC-5+	Extended	Derived scorecard	TBLxBSC
Additional scorecard					X	
Additional perspective(s)			X	X	(X)	
Additional dimensions in the 4 perspectives						X
All of the 4 perspectives		X		X	(X)	
Some of the 4 perspectives	X				X	

Table 1: Comparison among different types of Sustainable Balanced Scorecard

As shown in Table 1, the number and variety of Sustainability Balanced Scorecard architectures described in literature is somewhat large and allows to include sustainability in the strategies of organisations with different value systems and degrees of maturity in the adoption of sustainability practices: this research, therefore, lays the groundwork for the introduction of circularity measures in the Balanced Scorecard of various kinds of organisations.

2.2. Circular Economy

2.2.1. Circular Economy Strategies

2.2.1.1. Research paper selection

The primary objective of this paragraph is to comprehensively identify and gain insights into the leading Circular Economy strategies in the existing literature, with the ultimate aim of providing robust support for the selection of the CE strategies that will be functional to this Dissertation. In order to achieve this goal, the material collection was carried out through the database Scopus. The aim of the research was to find information about all the main CE strategies present in literature and implemented by companies. For this reason, to obtain accurate and refined results, a set of filters was configured, which confined the scope of the search to papers falling within the subject area of "Business, Management and Accounting" and the document type "Review". The search criterion adopted for this purpose was defined as follows:

TITLE-ABS-KEY ("circular economy" AND (strategy OR strategies)) AND (LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (DOCTYPE , "re"))

This led to the selection of a total of 88 research papers, which served as a starting point for the analysis. Subsequently, two screening phases were conducted. The first one was executed with a focus on the titles of the collected papers and led to the exclusion of a total of 71 papers due to the fact that they were either distant from the topic of interest or inclined towards industry-specific, country-specific, or case-specific analyses that did not align with the broader objectives of the study. The second step, instead, was based on the analysis of the abstracts of the remaining papers. This evaluation led to the exclusion of a further 6 papers, judged unsuitable for the following analysis. Indeed, they either did not mention specific CE strategies, they generically talked about sustainable practices instead of CE ones or only focused on the impacts of the CE on the value chain. Finally, the 11 papers were thoroughly read and 4 of them were not used in the study due to a lack of fit with the purpose of the research. Indeed, they tackled the topic of Circular Economy strategies but did not make use of specific models to classify them. This process was functional to ensure that the final set of 7 documents adhered closely to the desired parameters and objectives.

Subsequently, the snowballing technique was used to extend the data gathered in this phase of the work. This type of method refers to “using the reference list of a paper or the citations to the paper to identify additional papers”, that “could benefit from not only looking at the reference lists and citations, but to complement it with a systematic way of looking at where papers are actually referenced and where papers are cited” [40]. This way, 7 additional documents were used in order to make the literature review more precise and complete.

2.2.1.2. Literature State of the Art

The analysis of the selected papers enabled the identification of the main strategies and models studied and implemented within the field of the Circular Economy. As the literature review suggests, numerous authors recommend different classification frameworks to categorize existing CE strategies. 3 out of the 7 initially selected papers present the ReSOLVE framework as a way to categorize Circular Business Models (CBMs) [41] or to categorize operational actions which allow to put CE principles into practice [42]. The mentioned model presents 6 practices [43]:

- **Regenerate**: shifting to new types of material inputs such as renewable energy and secondary materials; preserving the health of the planet; returning biological resources to the biosphere;
- **Share**: sharing assets; prolonging product lifetime through actions such as reuse, maintenance and DfX (Design for X) practices;
- **Optimise**: fostering efficiency of both the product and the production process, possibly making use of digital technologies;
- **Loop**: remanufacturing, recycling and recovering products and materials;
- **Virtualise**: dematerializing the product;
- **Exchange**: replacing materials with more advanced ones and transforming processes through the use of new technologies.

Despite the popularity of the ReSOLVE model, among the analysed research papers, the "R framework" emerges as the most widely endorsed and utilized framework. It has been used for decades by several researchers and practitioners [11] and will be displayed in the following pages. However, before investigating the R framework, it is essential to acknowledge that multiple versions of this classification system exist. This diversity of R models offers organizations the flexibility to select the one that best aligns with their industry and the specific analysis they intend to conduct using the framework.

2.2.1.2.1. 3R framework

The **3R framework** is the simplest and most foundational classification of the CE strategies, comprising the principles of Reduce, Reuse, and Recycle. It is worth noting that this framework has played a pivotal role in shaping the legislation related to the Circular Economy, such as the Circular Economy Promotion Law of the People's Republic of China enacted in 2008 [44].

The **Reduce** strategy consists in "increasing efficiency in product manufacture or use by consuming fewer natural resources and materials" [11]. In this definition, two different stages of the product lifecycle are considered: the manufacturing and the usage phases. Indeed, as far as the production process is concerned, companies have the power to reduce the use of both raw materials and ancillary materials, with the objective of producing the same amount of output while consuming fewer resources. This can be accomplished by implementing efficiency measures to prioritise energy, water, land, and material conservation and by using renewable energy sources. Some examples of solutions are the use of solar energy, geothermal energy, and wind power as well as the adoption of advanced water-saving tools, processes, and technologies to monitor and reduce material consumption during production. Further to this, companies should also focus on the usage phase, since many products consume huge amounts of materials and energy during this stage. Additional solutions to implement this strategy are the virtualization of products and the use of digital technologies such as 3D printing, Internet of Things, Artificial Intelligence and Big Data & Analytics. So, in order to comply with established standards, manufacturers must create products that are both energy efficient and that require less material (e.g., water and detergents) when used by the end user. The Reduce strategy has an impact upstream in the supply chain, since it makes it possible to avoid the raw material extraction and all the possibly energy-intensive processes needed to work and refine the extracted resources. The benefits also occur later in the supply chain, since lower quantities of materials are landfilled and go through End-of-Life practices necessary to collect, sort, treat, and manage the waste.

Reuse is defined as the "reuse by another consumer of discarded products which are still in good condition and fulfil their original function" [11]. The product may require minimum condition monitoring, such as cleaning or repackaging, before the part or product can be used again. However, no disassembly is performed, and the product is not warranted [45]. This strategy reduces the consumption of new materials by making use of existing ones and, as a result, there may be a decrease in energy use, water use, pollution, and carbon footprint.

Recycle consists in "processing materials to obtain the same (high grade) or lower (low grade) quality" [11]. The aim of this strategy is to extend the lifespan of materials by reintroducing them back into the industrial processes. There are two types of recycling: *post-consumer recycling*, where the recycled materials come from used goods, and *pre-consumer recycling*, which is done after the manufacturing stage [45]. Moreover, the recycling process can be classified as *closed-loop recycling* or *open-loop recycling*. In the first case, the material will be recycled and used to make a new product with the same intended use; as a result, the recycled materials will re-enter the same supply chain as raw materials. Despite being conceptually the simplest form of recycling, it is the least used. Open-loop recycling, on the other hand, is in principle more complex but more common. It entails using at least a portion of secondary material to produce goods that perform different functions than the original one. When it comes to this kind of recycling process, two options exist: when the secondary material maintains the same properties as the original primary material, it follows the *same primary route* as the original material; instead, it follows a *different primary route* when "the secondary good replaces a different kind of material, energy or part while with the same or very similar function" [46].

2.2.1.2.2. 4R framework

While the 3R framework remains fundamental, the European Union has taken a step further with the introduction of the **4R framework**. In this expanded classification system, the Waste Framework Directive incorporates the original 3Rs—Reduce, Reuse, and Recycle—while introducing an additional strategy: "Recover" [47]. This extended framework reflects the EU's commitment to promoting comprehensive circular economy practices, emphasizing the importance of not only reducing, reusing, and recycling but also recovering valuable resources from waste streams.

The **Recover** strategy consists in recovering energy from waste through incineration or nutrients through biochemical (e.g., anaerobic digestion) or thermal treatments (e.g., pyrolysis) [48].

The 4R framework illustrates how circular models alter over time in response to the unique opportunities and difficulties presented by various regions and industries. It shows that a generalized approach is insufficient to address the transition from a linear to a circular economic model and that it must be reviewed and modified to fit specific contexts and goals, while keeping a solid theoretical grounding to CE principles.

2.2.1.2.3. 6R framework

Another possible framework to use is the **6R framework**. In this solution, I.S. Jawahir and R. Bradley acknowledge the importance of both the product design phase and the product rework [49]. Indeed, in addition to the mentioned 4 Rs, the Redesign and the Remanufacturing strategies are proposed.

The goal of the **Redesign** strategy is to "create new products or to modify existing ones to prolong their use, encourage circular behaviour and cycle them back to the system" [50]. It is a preventive strategy and, since it affects all subsequent stages of the product's life cycle, it serves as the foundation for all other CE strategies and can either act as a barrier or an enabler. The necessity of lowering resource consumption and minimizing waste generation must be taken into consideration during the design of processes, tools, products, and packaging materials. In order to achieve this, it is necessary to choose materials and implement design principles (DfX) that make it simple to recycle, disassemble, and degrade products while also ensuring their safety.

The **Remanufacturing** strategy involves the "re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many parts as possible without loss of functionality" [49]. Remanufacturing requires a great degree of work content (i.e., the disassembly of the product, the restoration and the replacement of certain components) and, for this reason, the resulting products have the same or a superior quality level. Indeed, the final product must be compliant with product specifications and customer requirements and must come with warranties that are equal to those of equivalent new products. Given the amount of work needed to implement this strategy, Remanufacturing is particularly suitable for those products whose recovered *cores* (the parts of the product to be remanufactured) still have an embedded value that is relevant both in respect to their market value and to their original cost. In addition to preserving materials, this strategy is particularly relevant in terms of energy savings, since it is estimated that the remanufacturing of a product requires only 20-25% of the energy used to produce the same product from scratch [51]. Moreover, it represents an advantage to the companies that receive the cores back, since they can obtain feedbacks on the reliability and durability of products. The activities required by a remanufacturing process include the disassembly of the product into its components, a cleaning process, a visual inspection to discard damaged parts, the remanufacturing of components and their reassembly with replaced parts.

2.2.1.2.4. 10R framework

Another, more comprehensive model is the **10R framework** [52] (Table 2, Table 3), which includes all the strategies of the 6R model together with additional ones. The 10 strategies (R0-R9) are classified within 3 clusters according to their target:

1. *Smarter product use and manufacture*: these strategies take place when the product is conceived, and they have the potential to make it circular and to enable other circular strategies;
2. *Extend lifespan of product and its parts*: these strategies are designed to keep finished goods and their components in the economy for as long as possible without eroding their value;
3. *Useful application of materials*: these strategies focus on biological and technical materials that are embedded in the product.

With respect to the 6R model, 3 additional strategies are considered, namely Repair, Refurbish and Repurpose. Moreover, the 6R framework's Redesign strategy has been differentiated into 2 separate strategies: Refuse and Rethink.

Target	Strategy
1	R0: Refuse
	R1: Rethink
	R2: Reduce
2	R3: Reuse
	R4: Repair
	R5: Refurbish
	R6: Remanufacture
	R7: Repurpose
3	R8: Recycle
	R9: Recovery

Table 2: The R10 Framework

The **Repair** strategy consists in fixing and replacing broken parts of a product to make it operational again by fulfilling its original function [11].

The **Refurbish** (or **Reconditioning**) strategy, consists in restoring a product and bringing it up to date [11]. Through this activity, some components are replaced, and the function of the product is upgraded.

The **Repurpose** strategy consists in using a "discarded product or its parts in a new product with a different function" [11]. It is an example of open-loop reuse, meaning that the repurposed product will enter a different supply chain with respect to the original one.

Refuse and Rethink are two preventive design strategies, meaning that they take place before the product comes to life. As a consequence, they influence all the following stages of the life cycle of the product, playing an important role in reducing environmental burdens as well as in increasing economic benefits.

Refuse means to "make a product redundant by abandoning its function or by offering the same function with a radically different product" [11], positively impacting resource consumption and waste generation.

The **Rethink** strategy consists in "making product use more intensive" [11]. This can be achieved by re-elaborating the idea behind the product, focusing, for instance, on sharing products, making them multifunctional and replacing them with non-material solutions. This last option is also called Servitization or Re-servitisation [53].

Strategy	3R	4R	6R	10R	Brief description
Refuse			X	X	Avoid certain materials and processes, but also make the product redundant or offer the same function through a different product
Rethink				X	Re-elaborate a product to maximise its utilisation and/or to dematerialise it
Reduce	X	X	X	X	Decrease the amount of materials, energy and waste related to the product
Reuse	X	X	X	X	Use the product that is still in good conditions and that can fulfil its original function for the second or further time
Repair				X	Bring a damaged product back to its original function
Refurbish				X	Restore a product to its original function and bring it up to date
Remanufacture			X	X	Reuse of components to make a new product with the same function
Repurpose				X	Reuse of products or their components to make new products with different functions
Recycle	X	X	X	X	Process materials to obtain a recycled material of the same or lower quality
Recovery		X	X	X	Incineration of materials for energy recovery or production of biochemical compounds

Table 3: Comparison between CE strategy frameworks

2.2.1.2.5. Framework comparison

Throughout this paragraph, a number of models were identified, thanks to an in-depth analysis of existing literature. First, the ReSOLVE model clusters the CE strategies into 6 groups instead of 10: Rethink and Reuse are clustered into the Share practice, while Remanufacturing and Recycling, which are fundamental CE strategies, are clustered into the Loop strategy. For what concerns the R models, the literature has proposed several frameworks which vary among each other in terms of number of R-strategies and in terms of the way in which they are clustered. For instance, in a new model that was proposed in 2009, which is a modified version of the mentioned 10R framework [45], the Reduce strategy is split into 3 groups: the Reduced impact of raw material use, the Reduced impact of manufacturing and the Reduced impact of usage phase. Again, another version of the 10R model has been proposed and, among the strategies that aim at better using materials, there is also a strategy called "Re-mine" [54]. This strategy, also called *landfill mining* or *urban mining*, consists in retrieving materials from landfill after they are discarded and become waste. This is done because some materials are present in huge amounts within landfills and their concentration is sometimes higher in landfills than in original mines [53]. In the 8R framework [50], Refurbish and Remanufacture strategies are clustered together, while an additional strategy (Re-circulate) is presented. The latter is not a proper strategy but refers to the logistics activities that are required to implement other CE strategies (i.e., collection, sorting and redistribution). Again, a different version of the 3R framework includes the strategies Reuse, Remanufacture and Recycle [43]. It goes without saying that by just looking at the results of this Scopus search, there are many and different R frameworks that can be used as classification tools for the CE strategies, starting with the basic 3R framework and evolving into more comprehensive models like the 4R, 6R, and finally, the 10R framework.

This means that there is plenty of room for selecting a model which best represents the richness and granularity of CE strategies, but at the same time does not excessively increase the complexity of the outcome. Following these principles, a choice on the model best suited for the aim of this Dissertation will be made in the next chapter, which will focus on structuring a performance management system which includes circularity metrics.

2.2.2. Circular Economy Indicators

This Dissertation would not be complete without a thorough investigation of Circular Economy indicators presented in literature. This is why this paragraph sets out to systematically identify and categorise CE indicators in existing literature, ultimately aiming at allowing companies to select a number of CE indicators most suitable to be included in their Performance Management Systems (such as the Balanced Scorecard). In order to achieve this goal, a literature review was carried out through the database Scopus. The search criterion adopted for this purpose allows to find any review paper about Circular Economy indicator(s), KPI(s) or metric(s) within the subject area of "Business, Management and Accounting", and is defined as follows:

TITLE-ABS-KEY ("circular economy" AND (indicator* OR kpi* OR metric*)) AND (LIMIT-TO (SUBJAREA , "BUSI")) AND (LIMIT-TO (DOCTYPE , "re"))

This led to the selection of a total of 27 research papers, which served as a starting point for the analysis. Subsequently, two screening phases were conducted. The first one was executed focusing on the titles of the collected papers and led to the exclusion of a total of 20 papers, most of which were either industry-specific or case-specific, thus did not align with the broader objectives of the study. The second screening phase was based on the analysis of the abstracts of the remaining papers: this evaluation led to the exclusion of further 2 studies, unsuitable for the following analysis. This process was functional to ensure that the final set of 5 documents potentially adhered closely to the desired parameters and objectives. Finally, the 5 papers were thoroughly read: 2 of them were rejected, as most of the metrics proposed did not align with the requirements set out for this review (did not focus on circular-specific or micro-level indicators), and 3 were included [55] [56] [45]. Subsequently, the snowballing technique was used to add one more research paper, found in the references of other documents previously analysed, to the data gathered in this phase of the work [57].

In order to create a comprehensive and orderly catalogue of micro-level circular measures, even when coming from different studies, some steps were followed. First, a selection of measures was made, discarding those with too weak of a link to circularity, those that were too industry-specific, and the ones not applicable at the strategic level of an organisation. The inventory was thus left with 152 metrics, which were then identified with their name, acronym, and a short description. Furthermore, a classification of the metrics according to multiple aspects was operated, and specifically: the circularity strategy or strategies they attempt to measure (according to the 10R framework described above), the perspective or perspectives of the BSC they are part of, the scope, and the type of measurement. In particular, the perspectives are the areas of the Balanced Scorecard: not only the four traditional ones were considered ("internal business process", "customer relationship", "financial", "learning and growth"), but also two additional perspectives ("sustainability", which, coherently with the Triple Bottom Line approach, considers environmental, social and economic sustainability, and "supply chain", which includes metrics related to collaboration with other actors of the supply chain), similarly to the Extended SBSC model cited above; each metric is also characterized by a type, depending on whether it is an "indicator" (a simple, numerical metric), a "questionnaire" (a set of quantitative and qualitative variables gathered in the organization in the form of multiple-choice questions, and often synthesized in one aggregated value), a "method" (a set of steps which allow the assessment of circularity aspects of a product or an organization), a "framework" (multiple indicators organized in a coherent structure), a "matrix" (the intersection of two indicators on two different dimensions, creating multiple quadrants to assess characteristics of a product or organisation), or a "toolkit" (a set of tools, often online, which allow a quick assessment of specific circular characteristics of a product or organisation).

By quantitatively analysing the final list of metrics, it is possible, therefore, to observe how many of those are part of which classification: firstly, the breakdown of metrics by CE strategy was performed (Table 4), revealing that a majority (65%) of the metrics are related to recycle (R8), followed at a distance by lifespan extension strategies (R3 – R7, remanufacture, refurbish, repair, repurpose and reuse), and then by the strategies related to product conception and design (R0 – R2), namely reduce, rethink and refuse;

lastly, 16% of metrics are related to recovery (R9). Note that the sum of percentages is more than 100% due to metrics often belonging to more than one strategy.

Target	Strategy	Number of related metrics	Percentage of related metrics
1	R0: Refuse	35	23,0%
	R1: Rethink	35	23,0%
	R2: Reduce	40	26,3%
2	R3: Reuse	45	29,6%
	R4: Repair	54	35,5%
	R5: Refurbish	58	38,2%
	R6: Remanufacture	62	40,8%
	R7: Repurpose	49	32,2%
3	R8: Recycle	99	65,1%
	R9: Recovery	25	16,4%

Table 4: Absolute and percentage distribution of CE metrics across the 10 CE strategies

Secondly, a quantitative analysis of the breakdown of CE metrics by BSC perspectives was conducted (Table 5), showing that an overwhelming majority of them (81%) belong to the "Internal Business Process" perspective. This is because most of the metrics that only relate to material flow, which are a significant share of the total number of metrics, were classified as belonging to this perspective. The remaining three traditional perspectives ("Customer Relationship", "Financial", "Learning and Growth") are much less represented among the metrics in literature (5-11%), and so are the two additional perspectives considered in this Dissertation ("Sustainability", 9% of indicators, and "Supply Chain", 11% of indicators).

CBSC perspective	Number of related metrics	Percentage of related metrics
Customer Relationship	13	8,6%
Financial	17	11,2%
Internal Business Process	123	80,9%
Learning and Growth	7	4,6%
Supply Chain	16	10,5%
Sustainability	13	8,6%

Table 5: Absolute and percentage distribution of CE metrics across BSC perpectives

The complete list of the metrics identified can be found in the Appendix, and will be very useful in the next chapter in order to fulfil the aim of this Dissertation.

2.2.3. Circular Maturity Level

An important aspect to consider when evaluating the implementation of the Circular Economy is the circular maturity level of companies. Organisations can, as a matter of fact, adopt CE practices at different times and with different degrees of pervasiveness within their strategic and operational levels. This difference depends on multiple factors, such as the industry in which a company operates, the size of the organisation and the availability of resources allocated for the transition from a linear to a circular business model, and is reflected on different dimensions of an organisation [58]. In particular:

- Value creation: in organisations with low circular maturity, low expectations are attributed to the value creation capability of circular innovations; as the circular maturity grows, however, more focus is placed on financially exploiting the newly introduced circular practices;

- Governance: the ability to shift from experimental to exploitative management of CE innovations and practices as circular maturity grows;
- People and skills: at early stages of circular integration into the business, CE development is advanced by a relatively small and driven group of employees; as circularity becomes more integrated into the business, so do circularity knowledge and skills;
- Supply chain and partnership: high-circular maturity organisations develop strong collaborative relationships with their suppliers;
- Operations and technology: in organisations with high levels of circular maturity CE practices are embedded into operational processes, technologies and data collection and analysis capabilities, thus allocating low operational costs and resource utilisation to CE practices;
- Product and materials: at advanced stages of circular maturity, Design for X practices are the standard across the organisation.

When considering all of these organizational dimensions and their evolution at different stages of circular adoption, a model describing organizational maturity levels for the CE can be developed. In particular, in this Dissertation the model by Nygaard Uhrenholt et al [58] was considered, which divides CE adoption into the following six levels of circular maturity:

- Maturity level: **none**.

In this case, there is no presence of circular awareness nor of circular practices: neither internal activities related to CE nor efforts to collaborate with other actors of the supply chain are in place. As a matter of fact, the circular economy is not included in the corporate strategy and the only measured circular aspects are functional to meeting regulatory requirements, as a way to avoid fines and additional costs.

- Maturity level: **basic**.

  Discussions on CE adoption are ongoing, and some limited and unintentional CE practices generate value. The circular effort is constrained to a number of simple internal initiatives regarding the reduction of waste generation, and CE still does not have an important role in the organizational strategy.

- Maturity level: **explorative.**

  In this scenario, "demonstration projects and pilots are initiated across different functions in the organisation" [58]: the implementation of CE is still limited to some internal projects, which do not involve upstream and downstream actors of the supply chain. Even though the circular economy remains second to profitability objectives and is not yet operationalised, it becomes part of the corporate strategy at the research and knowledge-building stage.

- Maturity level: **systematic**.

This is the maturity level where CE goes past the pilot stage and is finally integrated into all the company's operations. The implementation of the circular economy starts with employee training and product design; objectives are set, and investments are made to meet the expected efficiency and effectiveness goals; some collaboration projects with partners and knowledge institutions start to take place.

- Maturity level: **integrative**.

  In this case, the company integrates its CE practices and strategic focus with its supply chain, making collaboration a key value driver. The circular economy has become a crucial part of the corporate strategy, both for internal activities and for supply chain optimization. Circular loops are well-established and generate value thanks to investments in employee training activities and in an advanced infrastructure that enables the exchange of information, materials and products among the actors of the supply chain.

- Maturity level: **regenerative**.

  The organisation has embraced circularity to the core and "has achieved absolute decoupling of value creation and resource consumption" [58], both of which, therefore, are stand-alone company bottom lines. The circular economy is well-established both internally and in the relationship with other actors of the supply chain; employees' CE skills are prioritized and all decisions are functional to meeting CE principles.

2.3. Research opportunities

Through the extensive literature review conducted in this chapter, which can be mapped as shown in Figure 9, a few gaps in literature have been identified:

- A structured methodology for linking Circular Economy indicators with the company's strategy. This effort can only be found in literature when considering sustainability topics [36], but a comprehensive methodology with the same aim for Circular Economy is yet to be researched upon;
- Despite the existence of numerous research efforts aimed at developing Circular Economy indicators, a comprehensive model to order and systematize them according to features of the indicators (such as the circular economy strategies they measure) and of the organisations they are applied to (e.g., their circular maturity level) is not yet present in literature;
- Application of Circular Economy principles and indicators seems to still be almost exclusive to companies in the manufacturing sector, while there is limited literature effort to extend the application of Circular Economy to the services sector as well.

Starting from these gaps identified in literature, the following research questions, that this Dissertation will try to give an answer to, have been defined:

1. Research Question 1 (RQ1): *Can including indicators of Circular Economy into a company's Performance Management System support the company's circular transition? And if so, what is a theoretically founded and practically effective way of performing this integration?*
2. Research Question 2 (RQ2): *How can a classification of existing Circular Economy indicators be operated so that it takes into account both characteristics intrinsic to the indicators and characteristics of the companies they are applied to?*

These two research questions, that stem from the first two gaps in literature identified above (while the third one was considered to be out of the scope of this work), were deemed to be a good first step towards a more holistic approach to Circular Economy, one that does not limit itself to isolated initiatives but is truly embedded in organisations and companies. At the same time, as mentioned, further research is going to be required, as this work does not have the aim to completely fill a gap in knowledge that will require several further contributions and collective efforts to be explored more in depth.

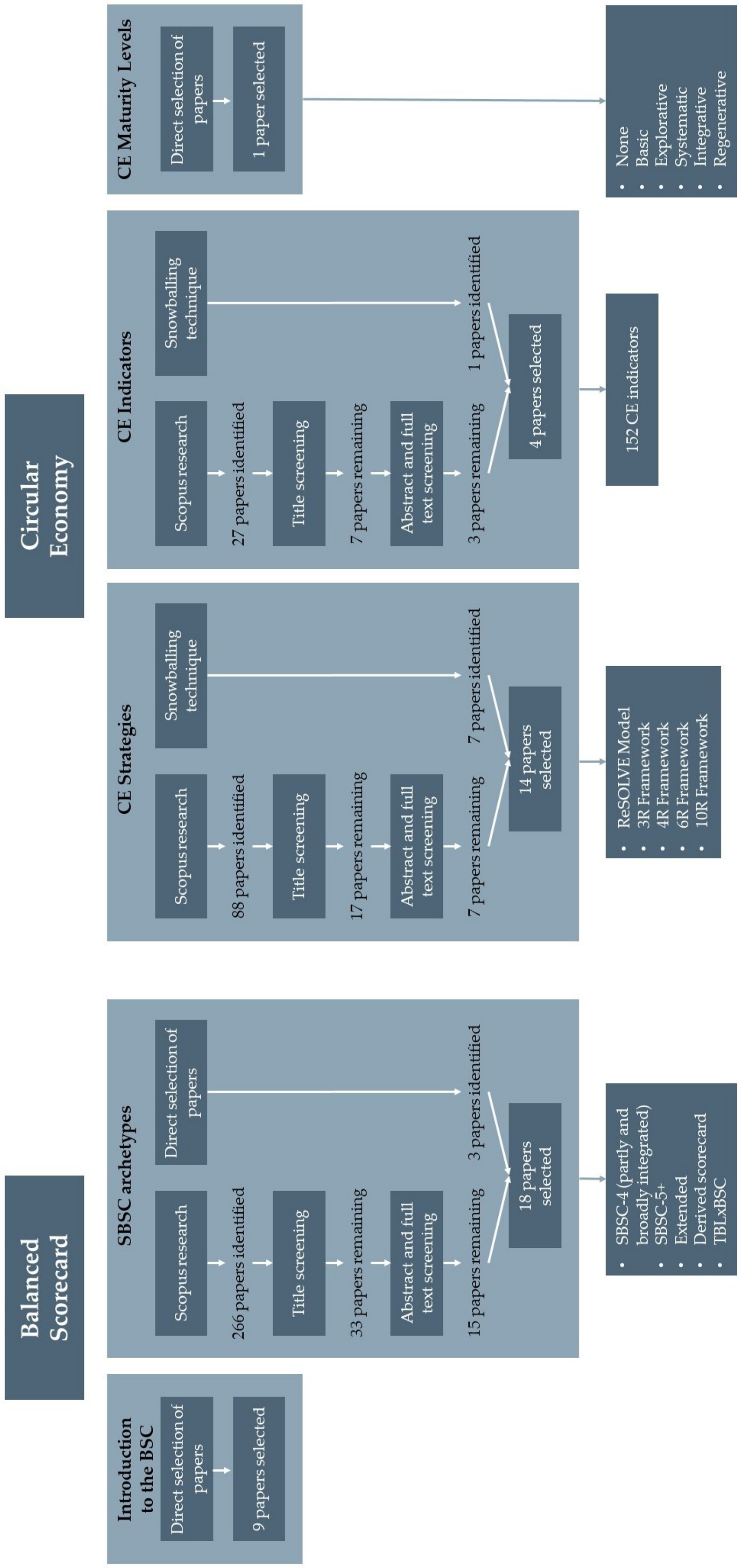

Figure 8. Literature streams mapping.

3 Model Development

3.1. Applicability of the model

The aim of this chapter is to develop a model that would allow companies belonging to different industries, adopting different CE strategies and with different CE maturity levels to integrate circularity metrics within their Performance Management Systems (PMS). In particular, the PMS that was considered for the modelling was the Balanced Scorecard, due to its characteristics, that were already discussed in paragraph 2.1: in particular, the BSC is extremely flexible, as it allows not only for the inclusion of circularity metrics but also for the redesign of its architecture in innovative and potentially disruptive ways. At the same time, the BSC is very widespread, both among practitioners (with more than a quarter of companies using it [29]) and scholars [30].

The starting point of the model development is the understanding of the needs to be tackled by the model and the kinds of companies and organisations that could make use of it: Circular Economy, as a matter of fact, is not yet widely adopted by companies and is often seen, not necessarily mistakenly, as a part of a wider sustainability strategy. This is why it is important to define the scope of the model both in terms of interaction between sustainability- and circularity-related indicators and of entities using the model, whether only circularity-focused companies and organisations or a wider and more diverse target group. Therefore, a number of alternatives were considered:

- Tailoring the model to circularity-focused companies: companies that have strong incentives to progress on the circular transition, such as legislative reasons (for example in the battery industry, which is being incentivized to reduce its intake of raw materials, both on geopolitical and supply security grounds [59]) or business model reasons, and thus see circularity as a primary business objective which will certainly benefit from a circularity Balanced Scorecard. This would mean, however, that the model would be centred around companies that already have a strong strategic focus on circularity (even if that does not necessarily mean that they have a high circular maturity level), thus without having a positive impact on CE uptake;
- Focusing the model on circularity as part of a wider sustainability strategy, thus creating a circular and sustainable Balanced Scorecard that would work for a wide range of companies. While this could be an interesting field for future research or practical applications, it would also be out of the scope of this Dissertation;
- Creating a model that encompasses companies with different CE maturity levels and degrees of strategic focus, while at the same time keeping a focus on

circularity metrics and thus excluding purely sustainability indicators. This approach was selected, as it allows to include the widest possible number of companies (thus supporting the further dissemination of CE) and at the same time can be adapted to different, existing BSC (or SBSC) architectures, while keeping the focus of the research on Circular Economy.

This is why this chapter is devoted to developing a Circularity Balanced Scorecard (CBSC) which shall be based on existing literature for BSCs and SBSCs and be feasible for the widest possible range of companies. At the same time, this model is not intended to be in any way exclusive or fixed: in fact, it is developed to be combined with different metrics and perspectives that were not considered in this Dissertation.

Another aspect to be addressed is whether this Dissertation should focus on companies with an advanced maturity level in the adoption of CE, the ones with a specific strategic focus on CE, or conversely, if the study should encompass organisations all across the spectrum of maturity levels. Also in this case, the most generic approach was selected, in order to be adaptable to the widest range of companies and therefore support companies with lower circular maturity levels in their CE development process: this means that all the circular maturity levels will be taken into account in the model and they will influence the model architecture, as shown in more detail in the following paragraph.

3.2. Model Development Process

In this paragraph, the steps undertaken to create the model will be explained in detail, starting from the results of the literature review and concluding with the proposed frameworks. The output of the model development process will be a theoretical model representing different possible architectures of the integration of Circular Economy metrics into companies' Performance Management Systems, and, in particular, Balanced Scorecards, in order to create several archetypes of the Circularity Balanced Scorecard (CBSC).

In order to create the aforementioned model, the following steps were taken:

- Firstly, as the Balanced Scorecard was selected as the Performance Management System of choice for this Dissertation (as discussed in the previous paragraph), an analysis of the structure and archetypes of the BSC and of the SBSC found in literature was conducted. In this way, it was possible to understand how traditional and sustainability KPIs should be organized within the four traditional areas of the BSC and the additional ones proposed by some of the SBSC archetypes. This work was functional to understanding how to create and structure Circular Balanced Scorecards starting from the architecture of BSCs and SBSCs, and how to complete them with CE metrics.
- The second step consisted in defining how to link different CBSC archetypes to different company CE maturity levels. Indeed, since the diversity of maturity

levels is reflected in companies' Performance Management Systems, different architectures of the Circularity Balanced Scorecard should be selected for different maturity levels of CE adoption. This finds evidence in the research by Hansen and Schaltegger [27], which does not limit itself to listing Sustainability Balanced Scorecard architectures, but also creates a hierarchy based on the "advancement" level in sustainability practices.

Thus, starting from the studied CBSC archetypes [27] [36] and the existing organizational CE maturity levels [58], the following model architectures were defined (Table 6):

- Maturity level: **none**.

  Since in this case there is no presence of circular awareness, a traditional BSC may be adopted. For companies with no CE maturity, the only circular aspects to measure might focus on meeting regulatory requirements. Consequently, a limited number of CE indicators could be present in their BSCs, each of which may be allocated to one of the four existing perspectives.

- Maturity level: **basic**.

  For this maturity level, only limited and unintentional CE practices are implemented. This means that some CE metrics may be integrated into some (and not necessarily all) of the four existing perspectives of the BSC, calling for a Partly Integrated CBSC-4 architecture, even though the new circular metrics might be added to the traditional BSC without a specific circular intention or strategic focus.

- Maturity level: **explorative.**

  For this maturity level, "demonstration projects and pilots are initiated across different functions in the organisation" [58]. This implies that metrics do not span throughout every perspective of the organisation, and at the same time that profit is still at the top of the value structure of the company, meaning that a Partly Integrated CBSC-4 architecture may be used at this level of maturity, with a specific focus on CE, unlike the basic maturity level.

- Maturity level: **systematic**.

  Here, CE is finally integrated into all the company's operations. Therefore, companies at this maturity level may adopt a Broadly Integrated CBSC-4, which would allow the inclusion of CE metrics in all four of the traditional perspectives of the BSC, showing that circularity is really embedded in the company's strategy and operations.

- Maturity level: **integrative**.

  In this case, collaboration along the supply chain becomes a key value driver. This means that the organisation may adopt an Extended CBSC, where circular metrics are embedded in the four traditional perspectives as well as in new perspectives, such as a "Circularity" perspective (which could include longer-term and less financially-driven circular indicators), a "Sustainability" perspective, and a "Supply Chain" perspective (which could serve to measure the level of collaboration and integration with the supply chain to implement, for instance, reverse logistics practices).

- Maturity level: **regenerative**.

  At this maturity level, CE becomes a crucial aspect of the corporate strategy, being considered at the same level as financial performance. This means that the organisation may adopt a Derived CBSC architecture, which allows to create a new, entirely circular BSC together with the traditional one, linking indicators to more than one bottom line: a financial bottom line and a circular or sustainable one.

	None	Basic	Explorative	Systematic	Integrative	Regenerative
Traditional BSC	X					
CBSC-4 Partly Integrated		X	X			
CBSC-4 Broadly Integrated				X		
Extended CBSC					X	
Derived CBSC						X

Table 6: Allocation of CBSC archetypes to different CE maturity levels

After linking the CBSC archetypes to the corresponding maturity level, therefore obtaining five distinct CSBC architectures, a thorough study and analysis of existing CE metrics was carried out. The aim of this step was to select relevant CE KPIs from literature and to classify them based on their characteristics. Indeed, some are complex and oriented towards the measurement of CE aspects that belong to companies that have a high circular maturity level; some others, instead, tackle organizational aspects that are common to companies across every level of circular maturity. Therefore, when selecting CE metrics for each model, a categorization based on the "minimum maturity level" allowed by each metric was operated, based on the minimum degree of pervasiveness of Circular Economy awareness and focus required inside a company or organization to adopt that specific metric, as described in Chapter 2. This means that more complex indicators, the ones that require a certain level of integration of Circular Economy in the company's operations, strategy, supply chain or even value system, were only included in the models related to more advanced maturity levels, considering their requirements (e.g., a metric that measures the degree of collaboration with the supply chain can only be applied to organisations whose circular maturity level is "integrative" or higher, and therefore have a circular focus in their exchanges with their supply chain).

Therefore, the indicators found in literature were assigned to the CBSC archetypes described in the paragraph above (one for every maturity level), respecting the minimum maturity level and the BSC perspective(s) assigned to each indicator. As an outcome of this process, five CBSC architectures were developed, with the complete list of metrics belonging to each architecture and perspective. This does not mean that all of the metrics displayed have to be applied in concrete cases, as further selection steps are going to follow for the practical application of the model.

In the tables following, one for each maturity level and thus one for each CBSC model, the acronyms of metrics will be shown, for the sake of brevity. The complete names and descriptions of the indicators can be found in the Appendix.

3.2.1. Maturity level: none

Since companies belonging to this maturity level lack circularity awareness and the implementation of circular practices, no CBSC has been proposed. However, those organisations may want to allocate a small number of CE indicators to the four existing perspectives of a traditional balance scorecard, and, in this case, a case-by-case selection will be performed.

3.2.2. Maturity level: basic

At this stage, a Partly Integrated CBSC-4 shall be used (Table 7). This means that, for the limited and unintentional circular projects in the organisation, a small selection of metrics belonging to not all of the four traditional BSC perspectives shall be made.

Internal Business Process	ADE, AF, AMRF, AMRR, ARBP, ARD, ARM, ARS, CDD, CDG, CEPI, CET, CI, CLC, CND, CRec, CRef, CRem, DEI, DMP, DSTR, DTC, DTP, ECD, eDiM, EDT, EOLI, EoL-RRs, EoLS, EPD, FRA, FRecM, FRemM, FRRM, HM, HSWM, HSWMF, IM, IVM, LCM, LFI2, LMT, LWP, MFRecP, MFeuRP, MIL, MRS, MT, NC, NDM, NDTa, NDTo, NM, NPD, NPNR, NRJ, NTD, NTF, OTDT, PBP, PHM, PL, PMF, PMS, PPR, PPT, PRecI, PReuI, PRP, PS, PSPS, PSWF, PT, RAF, RCU, RDP, RE, RecBCR, RecDI, RecF, REE, RemF, ReuBCR, ReuF, RGU, RIs, RMF, RP, RPI, RPMP, RPaU, RPlU, RRs, RSWMF, SCMSP, SD, SMC, SMJ, SPC, TBPPreU, TM, TMC, TNF, TNR, TPM, TQP, TRMM, TSWMD, WCRM, WGRP
Financial	CEI, CRec, CRef, CRem, PLCM, RRefP, RRemP, RRRC, RRRP, RURM, TAC, TSC, VRE
Learning and Growth	CDG, CET, CP, EEVC, IOBS, PR-MCDT
Customer Relationship	ACSO, CUE, FTlWOL, HSWM, HSWMF, MPAS, PHM

Table 7: Basic maturity level: Partly Integrated CBSC-4

3.2.3. Maturity level: explorative

At this maturity level, companies have implemented only some CE initiatives, most of which are still in the pilot phase. Moreover, those projects only pertain to certain organisational areas and functions, and the financial perspective still is of major importance to the company. Therefore, a Partly Integrated CBSC-4 (Table 8) has been selected for this maturity level.

Internal Business Process	ADE, AF, AMRF, AMRR, ARBP, ARD, ARM, ARS, CDD, CDG, CEPI, CET, CI, CLC, CND, CRec, CRef, CRem, DEI, DMP, DSTR, DTC, DTP, ECD, eDiM, EDT, EOLI, EoL-RRs, EoLS, EPD, **EPVR**, FRA, FRecM, FRemM, FRRM, HM, HSWM, HSWMF, IM, IVM, LCM, LFI2, LMT, LWP, MFRecP, MFeuRP, MIL, MRS, MT, NC, NDM, NDTa, NDTo, NM, NPD, NPNR, NRJ, NTD, NTF, OTDT, PBP, PHM, PL, PMF, PMS, PPR, PPT, PRecI, PReuI, PRP, PS, PSPS, PSWF, PT, RAF, RCU, RDP, RE, RecBCR, RecDI, RecF, REE, RemF, ReuBCR, ReuF, RGU, RIs, RMF, RP, RPI, RPMP, RPaU, RPlU, RRs, RSWMF, SCMSP, SD, SMC, SMJ, SPC, TBPPreU, TM, TMC, TNF, TNR, TPM, TQP, TRMM, TSWMD, WCRM, WGRP
Financial	CEI, CRec, CRef, CRem, PLCM, RRefP, RRemP, RRRC, RRRP, RURM, TAC, TSC, VRE
Learning and Growth	CDG, CET, CP, EEVC, IOBS, PR-MCDT
Customer Relationship	ACSO, CUE, **EM**, FTlWOL, HSWM, HSWMF, MPAS, PHM, **TBO**

Table 8: Explorative maturity level: Partly Integrated CBSC-4. Metrics underlined and in bold are only present starting with this maturity level

3.2.4. Maturity level: systematic

At the systematic maturity level, organisations have reached a complete circular integration in their operations. This means that a broadly integrated CBSC-4 shall be used (Table 9), selecting CE indicators for every one of the traditional four BSC perspectives.

Internal Business Process	ADE, AF, AMRF, AMRR, ARBP, ARD, ARM, ARS, CDD, CDG, CEPI, CET, CI, CLC, CND, CRec, CRef, CRem, DEI, DMP, DSTR, DTC, DTP, ECD, eDiM, EDT, EOLI, EoL-RRs, EoLS, EPD, EPVR, FRA, FRecM, FRemM, FRRM, HM, HSWM, HSWMF, IM, IVM, LCM, LFI2, LMT, LWP, MFRecP, MFeuRP, MIL, MRS, MT, NC, NDM, NDTa, NDTo, NM, NPD, NPNR, NRJ, NTD, NTF, OTDT, PBP, PHM, PL, PMF, PMS, PPR, PPT, PRecI, PReuI, PRP, PS, PSPS, PSWF, PT, RAF, RCU, RDP, RE, RecBCR, RecDI, RecF, REE, RemF, ReuBCR, ReuF, RGU, RIs, RMF, RP, RPI, RPMP, RPaU, RPlU, RRs, RSWMF, **SCI**, SCMSP, SD, SMC, SMJ, SPC, TBPPreU, TM, TMC, TNF, TNR, TPM, TQP, TRMM, TSWMD, WCRM, WGRP
Financial	CEI, CRec, CRef, CRem, PLCM, RRefP, RRemP, RRRC, RRRP, RURM, TAC, TSC, VRE
Learning and Growth	CDG, CET, CP, EEVC, IOBS, PR-MCDT
Customer Relationship	ACSO, CUE, EM, FTIWOL, HSWM, HSWMF, MPAS, PHM, TBO

Table 9: Systematic maturity level: broadly integrated CBSC-4. Metrics underlined and in bold are only present starting with this maturity level

3.2.5. Maturity level: integrative

At this maturity level, an Extended CBSC architecture is proposed (Table 10). CE strategies are implemented among and across all the organizational areas of the company and, moreover, they involve other players of the supply chain, both upstream and downstream. In order to keep track of this, in addition to the 4 traditional areas of the BSC, new ones are considered, e.g., the "Sustainability" perspective, which includes all those CE metrics that not only strictly relate to the circular economy, but also to the TBL (environmental, social and economic sustainability), and the "Supply chain" perspective, which considers the collaboration with other supply chain actors to implement CE activities such as reverse logistics.

Internal Business Process	ADE, AF, AMRF, AMRR, ARBP, ARD, ARM, ARS, CDD, CDG, **CEIP**, CEPI, CET, CI, CLC, **CM**, CND, **CPI**, CRec, CRef, CRem, DEI, DMP, **DPMP**, DSTR, DTC, DTP, ECD, eDiM, EDT, EOLI, EoL-RRs, EoLS, EPD, EPVR, FRA, FRecM, FRemM, FRRM, **FTcWOL**, HM, HSWM, HSWMF, IM, IVM, LCM, LFI2, LMT, LWP, **MCDA-ML**, **MCI**, MFRecP, MFeuRP, MIL, MRS, MT, NC, NDM, NDTa, NDTo, NM, NPD, NPNR, NRJ, NTD, NTF, OTDT, PBP, PHM, PL, PMF, PMS, PPR, PPT, PRecI, PReuI, PRP, PS, PSPS, PSWF, PT, RAF, RCU, **RDI**, RDP, RE, RecBCR, RecDI, RecF, REE, RemF, ReuBCR, ReuF, RGU, RIs, RMF, RP, RPI, RPMP, RPaU, RPlU, RRs, RSWMF, SCI, SCMSP, SD, SMC, SMJ, SPC, **SWOL**, **TBPPostU**, TBPPreU, TM, TMC, TNF, TNR, TPM, TQP, TRMM, **TSP**, TSWMD, WCRM, WGRP
Financial	CEI, CRec, CRef, CRem, **CT-RSC**, **EEVR**, PLCM, RRefP, RRemP, RRRC, RRRP, RURM, TAC, **TBC**, TSC, VRE
Learning and Growth	CDG, CET, CP, EEVC, IOBS, **MCDA-ML**, PR-MCDT
Customer Relationship	ACSO, CUE, EM, **FTcWOL**, FTlWOL, HSWM, HSWMF, MPAS, PHM, **SWOL**, TBO, **TSP**
Sustainability	**EEVC**, **ECVR**, **EEVR**, **HSWM**, **HSWMF**, **MCDA-ML**, **NJSOI**, **PHM**, **RRMSP**, **SCI**, **SCMSP**, **VRE**
Supply Chain	**ACSO**, **CPI**, **CSE**, **CT-RSC**, **CUE**, **DPMP**, **ECVR**, **MPAS**, **NJSOI**, **ReP**, **RRMSP**, **TBC**, **TBO**, **TBPPostU**, **TSP**

Table 10: Integrative maturity level: extended CBSC. Metrics underlined and in bold are only present starting with this maturity level, or belong in a perspective that has only been added starting with this maturity level

3.2.6. Maturity level: regenerative

At the regenerative maturity level, the organisation has now Circular Economy at the core of its value system: this calls for a Derived CBSC architecture (Table 11), allowing the organisation to have a CBSC structured around a financial goal and integrating a number of circular metrics, coupled with a new, entirely circular BSC, with a circularity strategic objective and only composed of the circular metrics of the first CBSC.

Internal Business Process	ADE, AF, AMRF, AMRR, ARBP, ARD, ARM, ARS, CDD, CDG, CEIP, CEPI, CET, CI, CLC, CM, CND, CPI, CRec, CRef, CRem, DEI, DMP, DPMP, DSTR, DTC, DTP, ECD, eDiM, EDT, EOLI, EoL-RRs, EoLS, EPD, EPVR, FRA, FRecM, FRemM, FRRM, FTcWOL, HM, HSWM, HSWMF, IM, IVM, LCM, LFI2, LMT, LWP, MCDA-ML, MCI, MFRecP, MFeuRP, MIL, MRS, MT, NC, NDM, NDTa, NDTo, NM, NPD, NPNR, NRJ, NTD, NTF, OTDT, PBP, PHM, PL, PMF, PMS, PPR, PPT, PRecI, PReuI, PRP, PS, PSPS, PSWF, PT, RAF, RCU, RDI, RDP, RE, RecBCR, RecDI, RecF, REE, RemF, ReuBCR, ReuF, RGU, RIs, RMF, RP, RPI, RPMP, RPaU, RPlU, RRs, RSWMF, SCI, SCMSP, SD, SMC, SMJ, SPC, SWOL, TBPPostU, TBPPreU, TM, TMC, TNF, TNR, TPM, TQP, TRMM, TSP, TSWMD, WCRM, WGRP
Financial	CEI, CRec, CRef, CRem, CT-RSC, EEVR, PLCM, RRefP, RRemP, RRRC, RRRP, RURM, TAC, TBC, TSC, VRE
Learning and Growth	CDG, CET, CP, EEVC, IOBS, MCDA-ML, PR-MCDT
Customer Relationship	ACSO, CUE, EM, FTcWOL, FTlWOL, HSWM, HSWMF, MPAS, **NCRC**, PHM, SWOL, TBO, TSP
Sustainability	EEVC, ECVR, EEVR, HSWM, HSWMF, MCDA-ML, **NCRC**, NJSOI, PHM, RRMSP, SCI, SCMSP, VRE
Supply Chain	ACSO, CPI, CSE, CT-RSC, CUE, DPMP, ECVR, MPAS, **NCRC**, NJSOI, ReP, RRMSP, TBC, TBO, TBPPostU, TSP

Table 11: Regenerative maturity level: derived CBSC. Metrics underlined and in bold are only present starting with this maturity level, or belong in a perspective that has only been added starting with this maturity level

3.3. Model Application

Once the theoretical models for each one of the identified CE maturity levels have been defined and populated with CE metrics, the theoretical phase of the development of the framework leaves the way to its possible practical applications, which vary case by case and company by company: this is because the theoretical approach followed until this point had the aim of being as widely applicable as possible, and therefore there is the need, for the practical application, that the model is narrowed down in scope.

With this objective in mind, two steps will be followed:

- Selection of the indicators that best fit the industry in which the company under consideration operates: this step is crucial in order to narrow down the list of indicators considering one of their "external" characteristics, that is, the sector; moreover, in the interview building phase it will be ensured that the indicators selected are actually relevant to the company's field of operation;
- Selection of indicators linking the Circular Economy strategy or strategies it measures to the ones adopted by the company being studied.

These two steps, which will be described in more detail in the following Chapter, are the starting point for the creation of a model that represents the practical application of the Circularity Balanced Scorecard.

4 Model validation: empirical study

This paragraph focuses on the empirical validation of the CBSC models that were just generated. The aim of this stage of *theory building* is that of understanding whether the designed theoretical models are actually of interest and useful to companies and organisations at some stages of Circular Economy adoption in order to further integrate the CE into company's strategy. The implementation of the empirical study was carried out by selecting companies with different CE maturity levels and conducting interviews and meetings with experts and managers working in those firms.

A CBSC architecture and a selection of indicators was proposed to each company: the former based on its current circular maturity level, while the latter was developed by filtering in two stages the complete set of indicators available at the maturity level of each company.

- Firstly, an assessment of the industry each company operates in was conducted. Indeed, each industry yields unique products and services, which, therefore, are difficult to compare in terms of economic and environmental impacts to the ones of different industries. Moreover, the circular economy is sector-specific, meaning that it cannot be implemented to the same extent to organisations operating in different sectors, "as opportunities, barriers and policy options typically differ significantly by sector" [60]. This is why for each company a selection of indicators was proposed that only considers those fit for the industry the company operates in. For this first filtering stage no fixed model was used to attribute indicators to industries: an empirical approach was preferred, determining case by case the sector of operation of the company and the indicators that best fit that sector.

- Secondly, the CE strategies implemented by the company were used to further filter the remaining CE metrics. As presented in Paragraph 2.2.1, multiple frameworks have been outlined in the literature review as potential classification tools: ReSOLVE, 3R, 4R, 6R, and the comprehensive 10R model. These frameworks present distinct strategies and differ in the number of strategies they use. In this study, it was decided to use the 10R framework (Table 12). Indeed, it is considered to be complete enough and suitable to most types of companies in terms of size, industry and adoption level of CE strategies. It also has the ability to encompass a wide variety of strategies, representing the richness and granularity of CE, without excessively increasing the complexity of the outcome. The allocation of CE strategies to the list of CE metrics carried out in Paragraph 2.2.2 was used in this stage to customise each model to the company considered based on the unique circular economy strategies it implements. Indeed, only the metrics linked to the CE strategies implemented by the considered companies were selected.

Target	Strategy	Description
1	R0: Refuse	Avoid certain materials and processes, but also make the product redundant or offer the same function through a different product
	R1: Rethink	Re-elaborate a product to maximise its utilisation and/or to dematerialise it
	R2: Reduce	Decrease the amount of materials, energy and waste related to the product
2	R3: Reuse	Use the product that is still in good conditions and that can fulfil its original function for the second or further time
	R4: Repair	Bring a damaged product back to its original function
	R5: Refurbish	Restore a product to its original function and bring it up to date
	R6: Remanufacture	Reuse of components to make a new product with the same function
	R7: Repurpose	Reuse of products or their components to make new products with different functions
3	R8: Recycle	Process materials to obtain a recycled material of the same or lower quality
	R9: Recovery	Incineration of materials for energy recovery or production of biochemical compounds

Table 12 [11]: The 10R Framework: classification of circular economy strategies

A step-by-step procedure for the structuring of the models will be presented in the next Paragraph, where the models are going to be applied to a small number of pilot companies.

4.1. Interview building

For the practical validation of the model presented in Chapter 3, a number of companies and organisations operating in different sectors, with different maturity levels and utilizing different CE strategies were selected, in order to best represent the wide range of applicability for which the model was built. A total of 6 companies and organisations took part in the model validation process. For each one of the selected companies, multiple preparatory steps were conducted prior to the interview:

- An analysis of the CE maturity level was carried out through the study of available sustainability reports, through web search, and, in some cases, through preliminary conversations with company specialists, making it possible to develop a customized model by selecting the most relevant archetype;
- Through the same documents, the CE strategies adopted by each company were identified. Since each CE metric was linked to one or more CE strategies (see Paragraph 2.2.2), it was possible to select only those KPIs related to the strategies implemented by the organisation;
- Lastly, the industry and fields of activity of each company were identified, and the CE metrics that did not match those were excluded, so as to obtain a set of metrics that better fits the empirical study and the companies under analysis.

Thanks to these three steps, it was possible to develop a CBSC model for each of the companies selected. It is important to note that the CBSCs designed only included indicators related to the Circular Economy, each in its respective perspective, and not more traditional financial and operational indicators and the hierarchical linkages among them, in order not to fall out of the scope of this Dissertation and to leave wider applicability to the models designed.

Once the model for each company was finalized, it was presented to one or more people with relevant sustainability and CE roles inside of the company in the form of a PowerPoint presentation (explaining the main goals and research objectives of the Dissertation and subsequently laying out the structure of the company-specific model) during a 45- to 60-minute videocall or in-person meeting.

The objective of the interview was to answer four main questions:

- "Can the Balanced Scorecard be an effective tool for CE integration in the company's strategy?": regardless of whether or not the company uses the BSC as its Performance Management System, it is important to understand if it could be a useful and interesting framework to link and integrate the Circular Economy within the organisation's strategy;
- "Does the company already measure any of the presented CE indicators?": since the interviewed companies have different CE maturity levels, there may be the possibility that organisations with a higher maturity level

already measure some CE metrics, while the ones with a lower maturity level do not. This is, therefore, an opportunity to understand whether the KPIs found in literature are of actual interest to companies and if companies have the necessity to measure additional metrics to the ones proposed;

- "Do the presented indicators work for the company and for its CE journey?": as part of the feedback session, it is key to understand whether the indicators selected to be part of the model can actually be of help in the company's circular transition or whether the selection is in scope, too wide or, on the contrary, too narrow;
- "Does the presented structure of the Circular Balanced Scorecard work for the company and for its CE journey?": this final question serves the scope of ultimately understanding whether the architecture of the CBSC presented in this Dissertation can support the integration of CE indicators inside the company's strategy through its Performance Management System, thus advancing the transition towards a Circular Economy.

In the following Paragraph, the companies selected for the model validation are going to be presented, together with the model that was designed for them and with the feedback given by the people that were contacted.

4.2. Interviews

4.2.1. Company A

Company A is a northern Italian packaging manufacturing company founded in the first half of the 20th century as a firm that operated in the marketing and resale of corrugated cardboard packaging items. Today, it is active in the corrugated cardboard sector with its production, logistics and services.

Over the past few years, the company has increased its focus on sustainability, since both the market and end consumers require it; however, only some limited sustainability and CE practices are implemented: it uses solar panels to generate renewable energy, manages water consumption and uses recycled raw materials for its products.

4.2.1.1. The proposed model

The first step of model generation consisted in the definition of Company A's CE maturity level. Thanks to a thorough analysis of the company website and documentation, Company A was assigned the **Basic CE Maturity Level**: even though it mostly uses recycled and recyclable materials as inputs, most of its activities related to the Circular Economy are unintended and focused on meeting market and legal requirements. The financial pillar of the triple bottom line is still the top priority and sustainability and CE are seen as a way to pursue profit. As a consequence of the maturity level choice, the **Partly Integrated CBSC-4** was chosen to assess the CE performance of Company A.

The second step consisted in defining which of the 127 CE metrics are most suitable to describe Company A's strategy and operations. To do so, the CE strategies pursued by the company were identified (**Reduce, Recycle**) and only the indicators linked to those strategies were kept (102). Of the remaining metrics, 93 were excluded due to the low relevance for the sector in which the company operates and due to the fact that they measure the performance in activities that the company does not implement. Finally, 9 metrics were included in the model proposed to the company (Table 13).

Internal Business Process	ARS, CDG, FRecM, FTcWOL, NDM, RDP, RMF,
Financial	VRE
Learning and Growth	-
Customer Relationship	ACSO, FTcWOL

Table 13: Proposed model for Company A

4.2.1.2. Company feedback

Below is reported feedback of Company A's technical director and of its QHSE supervisor.

Before showing the model, feedback on the choices made regarding the classification of Company A in terms of CE maturity level (Basic) and CE strategies implemented (Reduce, Recycle) was requested. For what concerns the CE maturity level, the interviewees judged the Basic maturity level to be low, claiming Company A's positioning to be in between the Basic and the Explorative levels. Regarding the second point, however, an additional strategy was suggested: Refuse.

Concerning the Balanced Scorecard, both the interviewees believe it is a useful tool to visualize and organize the KPIs of a company, and that Company A already uses a similar one, which however is different from the BSC. Moreover, after showing the CBSC model with the chosen indicators, they stated that its structure and the way in which indicators are assigned to each area is practical and clear, enabling companies to organize their indicators in an orderly way.

After showing them the indicators within the CBSC, the following feedback was given by the interviewees:

- Given Company A's business model, the customer relationship indicator **First technical wear-out life (FTcWOL)** is judged non relevant within the current business model of the company, which does not manufacture reusable packaging, but traditionally single-use products;
- Within the CBSC's internal business process perspective, the indicators **Number of Different Materials (NDM)**, **Fraction of Recyclable Material (FRecM)** and **Amount of Recycled Scraps (ARS)** were not considered relevant due to the fact that most of the products manufactured by the company are made of cardboard, the totality of which is sent to recycling facilities after the usage phase; moreover, all the scraps produced during the production phase are sold to recyclers. Company A already computes two indicators that were included in the model: **Recycled Material Fraction (RMF)** and **Rate of Defective Products (RDP)**.

- The financial indicator **Value-based Resource Efficiency Indicator (VRE)** and the customer relationship metric **Availability of Customer Support Option (ACSO)** have received positive feedback by the interviewees, who claim that they could be very useful and interesting, even if not yet computed by the company.

4.2.2. Company B

4.2.2.1. Company presentation

Company B is a multinational company headquartered in Italy that produces professional coffee machines. It was founded in 1912 and now it includes numerous brands. It has numerous manufacturing facilities and ten subsidiaries nationally and internationally, and hundreds of distributors to ensure technical support. It mainly produces three product categories: traditional coffee machines, fully-automatic coffee machines and coffee grinders. In 2021, Company B published its first sustainability report, describing how sustainability has become more and more important to the company over the past few years.

Some of Company B's goals in terms of sustainable development and CE implementation are the reduction of energy consumption in manufacturing, administrative, and service processes; the improvement of product energy efficiency during the usage phase; the reduction of Scope 1 and 2 emissions; designing and manufacturing products that decrease the use of virgin raw materials, increase the use of recycled and recyclable materials, and minimize resource waste; conducting assessments on the environmental impact of products; extending products' lifespan by providing them with a second life through reconditioning activities for certain components.

4.2.2.2. The proposed model

The first step of this phase consisted in the selection of a model. Through an analysis of its sustainability report and a web search, Company B was estimated to have an **Explorative maturity level**: some CE projects are soon to be implemented in few company's functions and, even though sustainability and CE belong to the corporate strategy, they are not prioritized in the same way as profitability. For this reason, the selected CBSC model is the **Partly Integrated CBSC-4**.

The second step in the model generation consisted in the selection of CE metrics based on the CE strategies implemented by the company. Since Company B only focuses on 3 out of 10 CE strategies (**Reduce, Repair, Recycle**), 14 out of 132 metrics related to the other 7 CE strategies were not considered.

The third phase consisted in the exclusion of 108 further indicators due to the fact that they measure operations that are not implemented by Company B (e.g., take-back and reverse logistics, material sorting and the use of hazardous materials in production) and activities that are not part of company's core business, therefore not being of interest in the PMS. After this stage, the remaining 10 indicators were included in the model (Table 14).

Internal Business Process	CET, FRecM, IVM, MFRecP, PRP, PSPS, RMF, SMJ
Financial	RURM
Learning and Growth	-
Customer Relationship	ACSO, MPAS

Table 14: Proposed model for Company B

4.2.2.3. Company feedback

Below is reported feedback coming from Company B's Sustainability Manager.

First of all, prior to presenting the model to the company, feedback was asked regarding the suggested categorization of Company B both in terms of CE maturity level (Explorative) and implemented CE strategies (Reduce, Repair, Recycle). For both aspects, the company deemed the categorizations appropriate, meaning that the CBSC architecture chosen (Partly Integrated CBSC-4) was well-suited for this organisation. Secondly, all the indicators shown to the organisation were considered useful in order to pursue the sustainability strategy the company has started to implement. However, all the metrics related to the amount of recycled and virgin materials included in the product ("Mass Fraction of Recycled Packaging" (MFRecP), "Input of Virgin Material" (IVM), "Recycled Material Fraction" (RMF)) can only be computed based on estimated values, which can be found in statistics databases: the company has now started to map its environmental impact, but the completion of this activity will take long, as coffee machines are made of numerous and complex components made of plenty of different materials. Therefore, Company B will be able to precisely compute the amount of recycled materials only after having contacted and worked together with all its suppliers.

Finally, some of the indicators included in the model (**Fraction of Recyclable Material (FRecM)**, **Recycled Material Fraction (RMF)**) are already computed by Company B, showing its interest in monitoring its steps in pursuing a circular business model.

4.2.3. Company C

4.2.3.1. Company presentation

Company C is a benefit corporation founded in the 90's, that aims at implementing industrial symbiosis by transforming what would be materials with no value into valuable inputs for companies operating in different sectors. Starting from third-party production scraps of aluminum, paper, rubber, plastics, fabrics, leather and other materials, Company C aims at implementing two kinds of activities: on the one hand, it leverages its know-how to start collaborations with other companies transforming their scraps and waste into customized final products (e.g., pens, notebooks, bags and design objects) through the use of its own innovative proprietary technologies, which guarantee that the recycled materials will have a performance that is almost equal to the one of virgin materials; on the other hand, it aims at connecting companies that generate production scraps to companies that could use those scraps as input materials in their processes: over the years, it has created a wide network of partners with different backgrounds that share their know-how, resources and production processes to create synergies that benefit all the actors of the supply chain and that would be otherwise impossible. Through research activities and advanced technologies, they aim to reduce the environmental impact of the entire value chain.

Company C also takes part in and promotes events to spread awareness around the topics of Circular Economy and Sustainability. It collaborates with universities, grants scholarships, and works together with cooperatives that include workers with disabilities, making social sustainability another goal of its corporate strategy.

4.2.3.2. The proposed model

The first step taken in the creation of the model was the definition of Company C's circular maturity level. After having studied its impact report and its website, the **Regenerative CE maturity level** was chosen as the one best describing Company C's business model. In addition to the Internal Business Process, Financial, Learning and Growth and Customer Relationship perspectives, two additional ones were selected: Supply Chain perspective and Sustainability perspective. This choice was made to reflect in the company's performance management system both its effort in creating a network of organisations that work together to implement the principles of the CE and its commitment in reducing as much as possible negative externalities coming from production processes and product usage.

Consequently, the **Derived CBSC** was taken as a starting point for the selection of the most suitable CE metrics. The identification of CE strategies implemented by the company (**Refuse, Rethink, Reduce, Repurpose, Recycle**) led to the exclusion of 18 out of 144 indicators from the analysis. Among the remaining KPIs, 114 more were considered unsuitable due to the fact that they either measured performance related to activities that the company does not implement (e.g., take-back and reverse logistics, maintenance, disassembly), they refer to products that have a more complex and different architecture from the one of Company C's products, or they did not fully adhere to the core business of the company.

The following table (Table 15) lists the 12 indicators submitted to Company C for the empirical test.

Internal Business Process	ARS, FRecM, MCDA-ML, MFRecP, NRJ, PBP, PRP, SCMSP
Financial	RRRP, VRE
Learning and Growth	MCDA-ML
Customer Relationship	ACSO
Sustainability	MCDA-ML, NJSOI, SCMSP, VRE
Supply Chain	ACSO, NJSOI

Table 15: Proposed model for Company C

4.2.3.3. Company feedback

Below is reported feedback of the founder and CEO of Company C.

Before showing the model to the company, feedback on the proposed classification of Company C, both in terms of CE maturity level (Regenerative) and in terms of CE strategies implemented (Refuse, Rethink, Reduce, Repurpose, Recycle), was asked. In both cases, the company considered the choices made suitable, meaning that the selected CBSC architecture (Extended CBSC) was the right one for this company. Then, the interviewee was shown the final model, in order to understand whether the identified indicators were actually of interest to Company C First of all, the CE maturity level and the type of CBSC selected were considered suitable by the company itself, meaning that the study conducted using firm's materials and website was complete and fitting. Most of the proposed metrics were considered useful by the interviewee, who, additionally, had the following feedback on how to improve the model:

- An indicator similar to the "Cost of user education on use and post-use opportunities" (CUE) and "Existence of Manual with environmental instructions" (EM), which are part of the list of indicators found in literature, should be included: on the one hand, it is necessary to educate partners on how the product they requested starting from their production scraps was manufactured and, on the other hand, to inform the final user about the origin and reuse/recycling potential of the product they received or bought.
- The metric "Product biodegradable packaging" (PBP) is not useful to Company C, since it does not use biodegradable materials in its packaging but only in its products. Moreover, the company delivers its customers packaging that is as recyclable as possible and that can be reused by the final user. Therefore, the following indicators may be added to the model: "Mass Fraction of Reusable Packaging" (MFReuRP) and "Packaging Recyclability per Product" (PRP).

Finally, Company C highlighted that most of the indicators can be measured for company-controlled production processes, but it may become difficult to compute them when products are manufactured in partners' plants.

4.2.4. Company D

4.2.4.1. Company Presentation

Company D, a multinational plant equipment manufacturer, was established in the second half of the 19th century in Switzerland. It has grown to being a global leader in technology and process engineering. The company operates in more than 100 countries, with dozens of manufacturing sites worldwide. Company D operates in two main sectors: Food & Feed, focused on providing solutions for processing foods and transforming grain into flour and animal feeds, producing pasta and chocolate, and in machinery and technologies for the production of energy-efficient vehicles and buildings.

Company D is committed to sustainability: it aims to make available solutions to reduce energy, waste, and water in its customers' value chains by mid decade. Furthermore, it has developed a pathway to reduce by more than half greenhouse gas emissions in its own operations by the end of the decade.

4.2.4.2. The proposed model

In order to elaborate a model that best fits Company D, multiple informal talks were held with the Sustainability Officer of Company D, and with other people in the Sustainability Team of the company, all of which, together with online research, allowed to define Company D's CE maturity level as **Integrative**, therefore allowing for an **Extended CBSC**. In addition to the Internal Business Process, Financial, Learning and Growth and Customer Relationship perspectives, an additional one was selected: the Supply Chain perspective. This selection was crucial in order to include indicators relevant for the circularity of Company D's customers in its CBSC, as the company's sustainability goals also take ownership for those of its customers: industrial machinery, especially in the food sector, can have a big impact on production yield and, as a consequence, on food waste.

Additionally, the CE strategies implemented by the company were selected, both the ones used in the technological cycle (so for Company D's own circularity in machines production: rethinking, repairing, and remanufacturing) and in the organic cycle (so for the Company D's food customers: reducing, refusing).

Subsequently, the CE indicators to populate Company D's CBSC were selected, based on the company's circular maturity level, the CE strategies adopted, Company D's industry, and more in general to the practices and activities that the company undertakes (which would make some indicators not relevant). As a consequence, 9 indicators (listed in Table 16) were selected and proposed to Company D.

Internal Business Process	RDI
Financial	RRemP, RURM, PLCM
Learning and Growth	MCDA-ML
Customer Relationship	ACSO
Supply Chain	SMC*, EoL-RRs*, NJSOI

Table 16: Proposed model for Company D

(*) Included in the Supply Chain perspective instead of the Internal Business Process one in order for Company D to measure its customers' Internal Business Process

4.2.4.3. Company feedback

Below is reported feedback given by the Sustainability Officer of Company D.

Before showing the model to the company, feedback on the proposed classification of Company D, both in terms of CE maturity level (Integrative) and in terms of CE strategies implemented (reducing, refusing, rethinking, repairing, and remanufacturing), was asked. In both cases, feedback was positive, even though some doubts remain over the real level of integration of Circular Economy into the day-to-day business of the company; nonetheless, according to the interviewee, the selected CBSC architecture (Extended CBSC) can be considered the right one for Company D. Subsequently, a few points were made as feedback on the final model:

- The Balanced Scorecard is perceived in industry as an academic tool, and Company D does not currently use it. Nonetheless, it can be useful as a way of organising the indicators among different perspectives;
- The Supply Chain perspective described in the model could be renamed into "Customer perspective", in order to highlight the narrower scope of the indicators integrated in it and focus Company D's attention to its customers even more;
- The indicators listed in the Supply Chain perspective are focused on recycling, while within the food industry, according to the interviewee, it could be even more helpful and relevant to differentiate and segment them according to the level in the food pyramid the materials are destined to.

Finally, the interviewee also suggested to widen the scope of the research to, or to leave space for future research on, how to integrate the model presented in this Dissertation with legislation and standards on the topic of Circular Economy (for example, TCFD), and how to integrate social metrics that are related to increased yield in food production.

4.2.5. Company E

4.2.5.1. Company Presentation

Company E, a multinational company based in Switzerland, was founded at the beginning of the 20th century. It has grown into a global leader in the manufacturing of building materials. The company operates internationally and employs approximately some tens of thousands of employees.

Company E operates in the industries of cement, concrete, their raw materials and related solutions. These segments encompass a wide range of products, including precast concrete, asphalt, mortar, and other building materials.

Sustainability is at the core of Company E's strategy. The company is committed to becoming a net-zero company, with 1.5°C targets validated by the Science Based Targets initiative (SBTi). Company E's approach to sustainability is oriented around climate, circular economy, nature, and people.

In terms of circularity, Company E applies the principles of "reduce, recycle, and regenerate" across its business. By mid decade, the company aims to recycle some millions of tons of construction and demolition materials into high-value products. By the end of the decade, it plans to increase recycled content in its cement and recycle tens of millions of tons of waste and byproducts for alternative energy and raw materials.

4.2.5.2. The proposed model

In order to elaborate a model that best fits Company E and best supports Company E's circularity journey, online research was conducted and an internal presentation was analysed, allowing to define Company E's CE maturity level as **Systematic** (as the main CE projects undertaken by Company E are now past the pilot stage and are mostly integrated into the business, but at the same time there is little integration of CE in its Supply Chain), thus structuring its CBSC as a **Broadly-Integrated CBSC-4** and integrating CE metrics into the four traditional perspectives: Business Process, Financial, Learning and Growth and Customer Relationship.

Additionally, a selection of CE strategies that best fit Company E was operated, resulting in the following three: reducing (as Company E's strategy is focused on the reduction of volumes sold, while increasing turnover), rethinking (business models) and recycling (construction and demolition waste).

Subsequently, the CE indicators to populate Company E's CBSC were selected, based on the company's circular maturity level, the CE strategies adopted, Company E's industry, and more in general to the practices and activities that the company undertakes (which would make some indicators not relevant). As a consequence, 11 indicators (listed in Table 17) were selected and proposed to Company E.

Internal Business Process	RRs, PPR, RMF, TMC, SMC, IVM, HSWMF
Financial	PLCM, RecBCR
Learning and Growth	CPI
Customer Relationship	ACSO

Table 17: Proposed model for Company E.

4.2.5.3. Company feedback

Below is reported feedback given by the Sustainability Specialist on Circular Economy at Company E.

Before showing the model to the company, feedback on the proposed classification of Company E, both in terms of CE maturity level (Systematic) and in terms of CE strategies implemented (reducing, rethinking, recycling), was asked. In both cases, feedback was positive, thus the selected CBSC architecture (Broadly-Integrated CBSC-4) can be considered the right one for Company E and the indicators can be potentially relevant. Subsequently, a few points were made as feedback on the final model:

- The Balanced Scorecard can be an effective tool for CE integration into the company strategy, even though at the moment Company E does not use it;
- Some of the indicators are currently already measured and monitored by Company E, in particular most of the ones in the Internal Business Process perspective (PPR, RMF, TMC, IVM, HSWMF);
- Most of the indicators proposed are potentially relevant and measurable by Company E, and could contribute to CE advancement within the company: RRs, PPR, RMF, TMC, SMC, IVM, HSWMF, PLCM, and RecBCR (this last one

could be of support especially when broken down by market, with the aim of showing regional differences and potentially create political and institutional awareness, which could be at the base of an advancement in CE uptake in the construction sector in the least developed regions); the indicators in the Customer Relationship and Learning and Growth perspectives are currently a bit too advanced for Company E and its markets; in the Financial perspective, an indicator measuring revenues from recycled materials could be added, together with the Material Circularity Indicator in the Internal Business Process perspective;

- The model presented is very relevant and forward-looking, and could definitely be a tool for CE advancement within Company E.

4.2.6. Company F

4.2.6.1. Company Presentation

Company F, a multinational company based in Germany. It has grown into a global leader in the specialty chemicals industry, operating in various markets, spanning from Aerospace, to Food & Feed to Electronics.

Sustainability is at the core of Company F's strategy. The company is committed to integrating sustainability into its strategic management process and increasing the proportion of attractive growth businesses in its portfolio with a clear focus on sustainability. Company F's approach to sustainability addresses the UN Sustainable Development Goals (SDGs) of particular relevance for the company.

In terms of circularity, Company F is significantly expanding its commitment to developing solutions for the circular economy. The company has set ambitious goals focusing on the circularity of plastics along the entire value chain. By the end of the decade, Company F aims to generate additional sales of hundreds of millions of euros from circular products and technologies. Furthermore, Company F intends to make greater use of defossilized raw materials based on recycled materials, biomass, and CO2. This commitment to circularity demonstrates Company F's dedication to better use of resources and sustainable development.

4.2.6.2. The proposed model

In order to elaborate a model that best fits Company F, online research was performed, which, together with a previous conversation with the Sustainability strategist at Company F, allowed to define the company’s CE maturity level as **Integrative**, therefore allowing for an **Extended CBSC**. In addition to the Internal Business Process, Financial, Learning and Growth and Customer Relationship perspectives, two additional ones were selected: the Supply Chain and the Sustainability perspectives.

Additionally, the CE strategies implemented by the company were selected: reducing (materials produced), refusing (replacing input materials altogether), rethinking (its business model), recycling, and recovering.

Subsequently, the CE indicators to populate Company F’s CBSC were selected, based on the company’s circular maturity level, the CE strategies adopted, Company F’s industry, and more in general to the practices and activities that the company undertakes (which would make some indicators not relevant). As a consequence, 17 indicators (listed in Table 18) were selected and proposed to Company F.

Internal Business Process	CEPI, TRMM, RMF, TMC, SMC, FRRM, HSWMF
Financial	RecBCR, RRRC, PLCM
Learning and Growth	CPI
Customer Relationship	ACSO, CUE
Supply Chain	CSE, NJSOI
Sustainability	SCMSP, SCI

Table 18: Proposed model for Company F.

4.2.6.3. Company feedback

Below is reported feedback given by the Sustainability Strategist of Company F.

Before showing the model to the company, feedback on the proposed classification of Company F, both in terms of CE maturity level (Integrative) and in terms of CE strategies implemented (reducing, refusing, rethinking, recycling, and recovering), was asked. In both cases, feedback was positive, even though the integration of CE into the business is not at an advanced stage and some CE strategies do not fully apply (recovering is not really a strategy Company F leverages on, especially given that pyrolysis is considered to be a form of recycling, and refusing is not applied internally, but is enabled in the supply chain thanks to Company F solutions), thus the selected CBSC architecture (Extended CBSC) can be considered the right one for Company F and the indicators can potentially be considered relevant. Subsequently, a few points were made as feedback on the final model:

- The Balanced Scorecard is an interesting tool, and it could support Company F's circular transition, especially when considering its structure, based on multiple indicators clustered together: it allows to show CE in its many facets, while at the same time keeping a coherent and orderly structure;
- Some of the indicators are currently already measured and monitored by Company F, in particular TMC, SMC, FRRM, HSWMF (Company F has legal requirements linked to these indicators), RMF (only packaging, due to regulatory requirements), RRRC, SCMSP (Company F receives a strong pull from the value chain for sustainability-certified materials); some indicators are kept track of in a more qualitative way, such as the ones included in the Customer Relationship and Supply Chain perspectives;
- Most of the indicators proposed are potentially relevant and measurable by Company F and could contribute to CE advancement within the company: not only the ones that are already measured but also the CPI, which could be monitored in a more qualitative way. Regarding the SCI, however, the feedback was negative (the interviewee's feedback was to keep sustainability and circularity on two different and separate levels)
- The model presented is relevant for Company F and its Circularity journey. It could also potentially be expanded by looking for ways to integrate it with legislation on Circularity.

4.3. Empirical analysis discussion

The starting point for the empirical validation of the model was the selection of a number of companies to best represent the target of the Dissertation: in particular, the aim was to gather companies from all across the spectrum of maturity levels, in order to keep the scope of the work broad and widely applicable. The companies that were selected are Company A, cardboard packaging manufacturer, Company B, professional coffee machines manufacturer, Company E, construction materials manufacturer, Company D, industrial machinery manufacturer, Company F, specialty chemicals company, and Company C, byproducts reprocessing company. For each company, a CE maturity level, the corresponding CBSC architecture (Table 19) and a number of circular metrics, divided by CBSC perspective, were selected.

Thanks to the feedback obtained by the interviewed firms, it was possible to draw the following conclusions.

As shown in Table 20 some of the interviewed companies acknowledge the Balanced Scorecard as a valuable tool for visualizing and organizing their KPIs. However, while some interviewees were familiar with the existence of this tool, they lacked deep knowledge of this concept; none had incorporated it in their Performance Management System.

Moreover, before presenting the model to each company, the fitness of the selected CE maturity level was tested, and all the companies part of the study agreed that the maturity level identified well described their current state of CE implementation.

Looking at the metrics proposed, a number of them were already integrated among the ones measured by the companies, mainly due to legislative reasons, circular economy adoption in the company, and for external communication purposes. This information serves as a proxy for evaluating the model’s suitability, as it validates the effectiveness of the model in assessing organizational CE performance: therefore, this could mean that the selection of indicators operated as part of this Dissertation is aligned with the companies’ goals and targets in terms of circularity.

Furthermore, the companies were asked about the potential relevance of the indicators selected for their CE journeys: most of the metrics (72-80%) were deemed as fitting, while the remaining part was considered non relevant. This slight inconsistency in the selection of CE metrics highlighted two main issues:

- Some indicators are not fully consistent with the business of the interviewed companies. The primary cause could lie in insufficient availability of resources on circular practices and on the business of the companies: prior to the empirical analysis, information about the organisations was gathered on the Internet, lacking direct discussion with company’s employees. As a consequence, some facets of the firms were still unclear when the model was built, justifying the discrepancy in the selection of the metrics.

- The indicators selected from literature are generic: this choice was made to extend the model to as many companies as possible, regardless of the sector they operate in. As a consequence, there is a lack of metrics suitable to measure specific performances related to some sectors. For instance, Company A manufactures cardboard packaging, which is a simple product made of few components and few materials. The metric "Number of Different Materials" (NDM) was proposed to the company, but it was judged unsuitable due to the fact that cardboard represents the overwhelming majority of the product's weight and the other materials used are irrelevant in percentage. It could therefore be important to further extend and update the list of metrics to include sector-specific ones as well.

In general, feedback from the companies was very positive: all of those that gave feedback on the CBSC model as a whole described it as relevant for them and potentially able to drive Circular Economy adoption and/or dissemination inside the company. This means that, according to the companies taking part in the validation phase, the scope of the thesis is well fulfilled by the model presented.

At the same time, they gave further input that in some cases exceeds the scope of this Dissertation but could be useful as a starting point for future research: how to integrate legislative requirements in this model and how this model relates to CE measurement standards, if any.

Company	Sector	CE maturity level proposed	Does the proposed CE maturity level actually suit the company?	CBSC archetype adopted
Company A	Cardboard packaging	Basic	Yes, albeit a bit too low	Partly Integrated CBSC-4
Company B	Professional coffee machines	Explorative	Yes	Partly Integrated CBSC-4
Company E	Construction machinery	Systematic	Yes	Broadly Integrated CBSC-4
Company D	Industrial machinery	Integrative	Yes, albeit a bit too high	Extended CBSC (CBSC-5)
Company F	Specialty chemicals	Integrative	Yes, albeit a bit too high	Extended CBSC (CBSC-6)
Company C	Byproducts reprocessing	Regenerative	Yes	Derived CBSC

Table 19: Company's sector, CE maturity level and CBSC archetype.

Company	Can the Balanced Scorecard be an effective tool for CE integration in the company’ s strategy?	Does the company already measure any of the presented CE indicators?	Do the presented indicators work for the company and for its CE journey?	Does the presented structure of the Circular Balanced Scorecard work for the company and for its CE journey?
Company A	Yes	2 out of 9	4 out of 9	Yes
Company B	-	2 out of 10	10 out of 10	-
Company E	Yes	5 out of 11	9 out of 11	Yes
Company D	Yes, albeit a bit academic	-	8 out of 9	-
Company F	Yes	7 out of 17	7-12* out of 17	Yes
Company C	-	-	11 out of 12	-

Table 20: Empirical analysis results.

(*) The number varies depending on the way the indicators are measured (according to the company, some indicators could be monitored in a more qualitative way)

5 Conclusion

This last chapter has the aim of presenting the conclusions to this work, while at the same time elaborating the main outcomes both from a literature and managerial standpoints, and future research opportunities. The first paragraph of the chapter revisits the motivations driving this research and summarises the main findings giving an answer to the two research questions. The following paragraphs discuss the main contributions given to the literature in the field by this work, both in terms of indicators and of structure of the Circularity Balanced Scorecard, the possible managerial applications of the Dissertation, and, lastly, the limitations of the study (also with regards to the feedback received) and the space for future research.

5.1. Rationale of the work, research approach and conclusions

The concept of Circular Economy has come to have great relevance in recent years, and, despite the huge importance of measurement in corporate governance, a structured and comprehensive approach to micro-level CE measurement and its application to corporate strategy has yet to be developed and agreed on. Many studies have outlined this gap in knowledge [23], which prevents companies and organisations from having a strategic understanding of Circular Economy, which, instead, stays limited to isolated initiatives.

This Dissertation had the aim of addressing some of those gaps, setting off with a Literature Review aimed at having a better ground understanding of the two following main research lines:

- The Balanced Scorecard: the structure of the traditional Balanced Scorecard, and the ways the BSC has been adapted and expanded to integrate Sustainability indicators;
- The Circular Economy, with a focus on the following topics:
  - Circular Economy Strategies
  - Circular Maturity Levels
  - Circular Economy Indicators

The Literature Review section also allowed the identification of gaps in the current body of knowledge, through which the following research questions were defined:

1. Research Question 1 (RQ1): *Can including indicators of Circular Economy into a company's Performance Management System support the company's circular transition? And if so, what is a theoretically founded and practically effective way of performing this integration?*

2. Research Question 2 (RQ2): *How can a classification of existing Circular Economy indicators be operated so that it takes into account both characteristics intrinsic to the indicators and characteristics of the companies they are applied to?*

In order to answer the two research questions mentioned above, the Model Development section set off to build on the already-existing Balanced Scorecard framework by elaborating multiple Circularity Balanced Scorecard archetypes, one for each circular maturity level that companies can possess. Subsequently, each of the CBSC archetypes was populated with Circular Economy indicators, thus starting to bridge the theoretical and practical gaps between company strategy, under the quantitative form of the Balanced Scorecard, and CE indicators, and producing five different CBSC architectures with different perspectives and a number of indicators among which to select, partly answering RQ1. The indicators used for the model were gathered from multiple studies available in literature, and were then enriched with a more complete classification framework built on both internal characteristics of each indicator (CE strategies measured, BSC perspective analysed…) and characteristics of the companies it can be applied to (the minimum circular maturity level, for example), answering to RQ2. Lastly, the theoretical model developed was validated with 6 different companies operating in different industries and with a wide range of circular maturity levels: during this step, a CBSC model with CE indicators was designed for each of the companies selected, and feedback on the model and on the indicators was gathered.

The feedback given by the companies selected was positive both in terms of metrics (with 72-80% of the indicators included in the models that were deemed relevant by the companies for their circularity journey) and in terms of CBSC architecture (all of the company representatives who gave feedback on the CBSC expressed a positive view of the model and its ability to drive CE forward in their companies). This means that, at least according to the companies selected, the model elaborated and presented in this Dissertation could be a tool to further Circular Economy integration within company strategy, which gives an answer to RQ1, paving the way for the transition towards fully circular business models.

5.2. Theoretical implications

The work elaborated in this Dissertation stems from previous research within the fields of Circular Economy (in particular, its strategies [52] [11], maturity levels [58], and indicators [55] [56] [45]), and of the Balanced Scorecard [24] [25] and its sustainability-focused architectures [36] [27], and aimed at contributing to the field with new insights and with the development of a Circularity Balanced Scorecard, whose practical relevance was validated with companies, on the basis of an extensive list of CE indicators.

Firstly, the Dissertation performs a review of multiple existing studies on Circular Economy indicators, drafting a comprehensive list of those indicators and operating a classification based on both internal criteria (e.g., CE strategies measured) and external, or company-related, criteria (e.g., BSC perspectives assessed).

Secondly, this work suggests that one of the ways companies can follow to integrate Circular Economy in their strategies is by integrating CE indicators in their Performance Management Systems and, in particular, in their Balanced Scorecard. Therefore, based on existing research on Sustainability Balanced Scorecards, different archetypes of the Circularity Balanced Scorecard were developed, suggesting that the architecture used by a company should be based on its circularity maturity level, as CE indicators interact differently with existing financial and operational indicators depending on the structure of the BSC or, in this case, of the CBSC.

Lastly, the results of the validation phase were positive, as they confirmed that the CE indicators aggregated in this work are relevant for the further development of CE in companies, and that the Circularity Balanced Scorecard can be one of the tools of the integration of Circular Economy into companies' strategies.

5.3. Managerial implications

This study holds significant potential for enhancing managerial practices by offering a comprehensive methodology to integrate the circular economy into the Performance Management System of companies across different sectors and maturity levels.

First of all, a crucial aspect of this study lies in the identification of the CE maturity level, representing the initial stage in formulating the proposed model. This step helps companies foster awareness on the AS-IS situation of their business in terms of pervasiveness and implementation of the circular economy, delineating current practices and highlighting the necessary steps to advance towards a higher CE maturity level.

Secondly, this study provides companies with a curated list of useful CE indicators, systematically classified in a way that facilitates easy selection by organisations based on specific measurement and external communication needs: the abundance of indicators in literature may overwhelm companies during the selection process, therefore, having a comprehensive metrics list encompassing different aspects of the circular economy may help companies find the most relevant ones more easily.

Thirdly, the Model, being based on the Balanced Scorecard, allows managers to have a better understanding of Circular Economy as a whole, providing a visual and practical representation of its multiple dimensions, while at the same time offering a framework that allows to link CE indicators to more familiar financial and operational metrics.

Lastly, the model proposed in this study helps companies integrate the circular economy into the existing Performance Management System and, consequently, into their corporate strategy. This is crucial as companies worldwide face the imperative of transitioning towards more sustainable and circular business models, but often lack sufficient guidance in this shift. The model presented here provides support in understanding what and how to measure it, filling a critical gap in the adoption of circular economy by companies.

5.4. Limitations and further research

A first limitation to the implementation of the models proposed is the fact that, despite being widely used and positively considered by scholars and companies, and despite being the most adopted Performance Management System, the BSC is still far from being adopted by every company. This is a major limitation in the study but also represents a starting point for future research on the integration of circular economy indicators in other Performance Management Systems.

A further limitation is represented by the list of indicators used to create the model: the metrics were selected with the aim of keeping the model as scalable as possible, therefore excluding from the analysis indicators that were sector specific. This, however, may lead to the exclusion of metrics that would have been more suitable for companies operating in certain sectors. Moreover, the list of indicators created is not exhaustive, therefore leaving space for future integration of new metrics.

Additionally, given the importance that the circular economy has been gaining nowadays, new norms and policies will be defined by policy makers to foster and accelerate the transition from a linear business model towards a circular one. It could therefore be an interesting research opportunity the expansion of the model presented in this work to allow integration with present and future legislative requirements and standards, as suggested by some of the interviewed companies.

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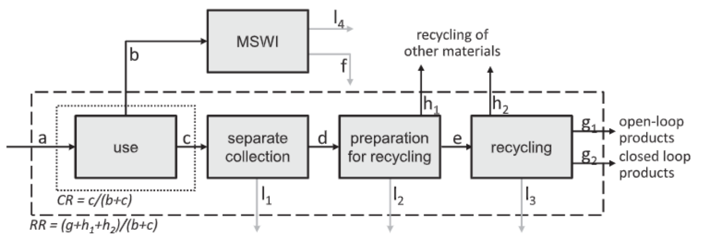
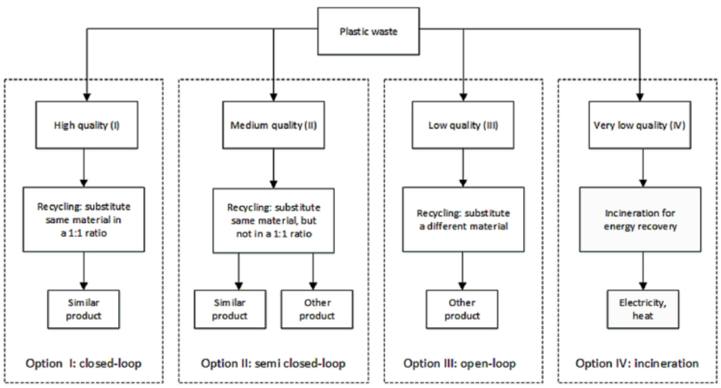
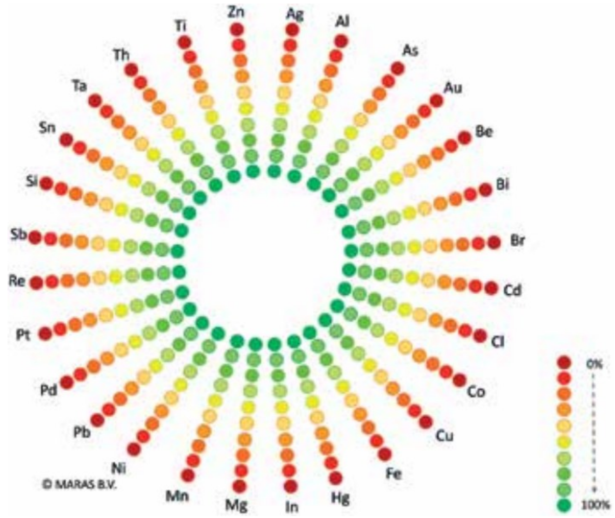
A Appendix A

#	Indicator	Acronym	Description
1	Recycling Rates	RRs	Indicator for the circulating behaviour of materials. It is often used as measure for the degree of circularity of an economy. RRs measure the available secondary resources produced from recycling processes, both as an open-loop and a closed-loop recycling processes. 
2	End-of-Life Recycling Rates	EoL-RRs	Percentage of a metal in discards that is actually recycled.
3	Circular Economy Performance Indicator/Recyclability Benefit Rate indicator	CEPI	Formula: the ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to quality, assuming option I (closed-loop recycling) is better, and option IV (incineration) is less preferable. The environmental benefits are expressed in terms of natural resource consumption, computed using the LCA-approach. 

<table>
<tr><td>4</td><td>Reuse Potential Indicator</td><td>RPI</td><td>The RPI indicates how much a material is “resource-like” rather than “waste-like” according to the current available technologies, in a scale from 0 (100% waste-like) to 1 (100% resource-like) based on the weight that can be reused on the total weight.</td></tr>
<tr><td>5</td><td>Recycling Indices for the CE</td><td>RIs</td><td>The Material-RI expresses the recycling rate of individual elements for the processing flow sheet of a specific product or redesign. The weighted average of the individual recycling rates provides the basis for the overall recycling rate as presented by the overall RI.


</td></tr>
<tr><td>6</td><td>Circular Economy Indicator Prototype</td><td>CEIP</td><td>15 variables linked to the EMF CE principles are identified and a question is defined for each variable. Using the questionnaire, that presents a weight for each possible answer, the value of the CEIP is computed. The questions are grouped by lifecycle stage, with a single aggregated score showing the ‘circularity’ of the product. The CEIP is initially intended to be used by manufacturing and/or retail companies of tangible goods with access to bill of materials to evaluate the performance of their products.</td></tr>
<tr><td>7</td><td>Circularity Potential Indicator</td><td>CPI</td><td>Through a guided questionnaire of twenty attributes (ATT#) desired for a circular economy, that are based on and grouped within the four building blocks (BB#) of circular economy defined by Ellen MacArthur Foundation, the CPI aims at evaluating the circularity potential of industrial products (during design, re-design or benchmarking phases) as well as providing keys for improvement and monitoring the circularity of products and businesses practices.

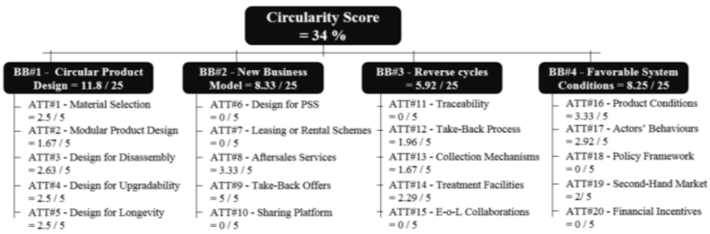
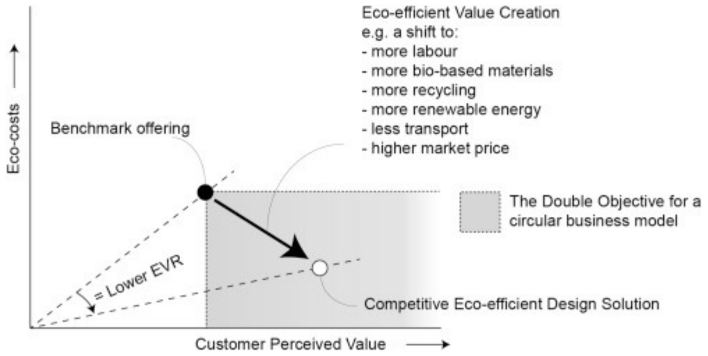
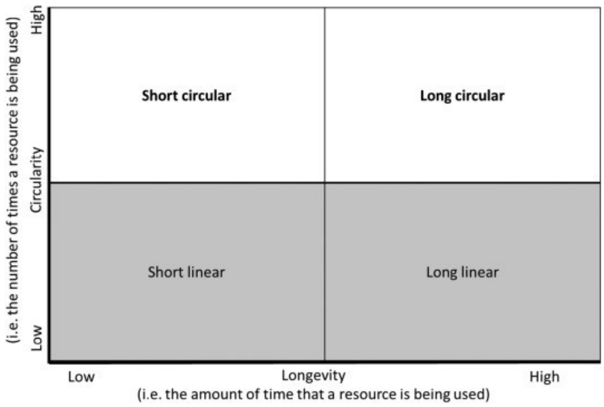


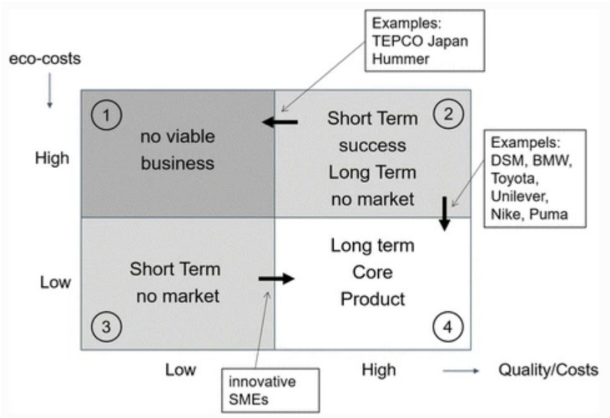
Figure 3. Application of the framework on the case study. Overview of the results.</td></tr>
</table>

8	Product-Level Circularity Metric	PLCM	The value ranges between 0 and 1 (0% and 100% of recirculated parts). $$C = \frac{economic\ value\ of\ recirculated\ parts}{economic\ value\ of\ all\ parts}$$
9	Circular Economy Index	CEI	The economic value is considered: market value. It measures recycling rates, excluding all other circular economy effects and loops. $$\text{CEI} = \frac{\text{Material value recycled from EOL product(s)}}{\text{Material value needed for (re–) producing EOL product(s)}}$$
10	Circularity Index	CI	$$\alpha = \frac{Recovered\ EoL\ material}{Total\ material\ demand}$$ $$\beta = 1 - \frac{Energy\ required\ to\ recover\ the\ material}{Energy\ required\ for\ primary\ production}$$ α = Material quantity preservation, accounts for both stock preservation and dissipative losses β = Material quality preservation, expressed as energy comparison Circularity Index (CI) = $\alpha\beta$, maximum value = 1
11	Closed Loop Calculator	CLC	Kingfisher Circularity Calculator is used to establish how products are able to close the loop. It uses 10 questions to measure how closed loop a product is. Criteria include what the product is made from, if it can be rented or repaired and whether it can be disassembled into component parts or materials. A product with 'excellent' closed loop credentials will achieve a rating of above 75% and a 'very good' product will rate above 55%. Initial baseline for the CEIP.
12	Circular Pathfinder	CP	Identify the most suitable circular pathways for the product one company designs and manufactures, in just a few minutes (Strategy ideation tool, Project definition phase, No preparation required, Approximately 15 minutes needed to complete)
13	Input-Output Balance Sheet	IOBS	A pilot project to measure the product's circularity and evaluate new strategies for businesses, including a beta tool to allow companies to measure the circularity of its products. Through an input-output assessment of all the resources used for the installation, maintenance and disposal phases, the types of resources used (from renewable and non-renewable sources) have been quantified and evaluated, as well as the circularity of the materials used (recycled, permanent recycled and virgins materials). Thanks to economic evaluations, it was possible to identify the improvement actions to be applied to the components of the plant in order to improve the circularity of the plant.

14	Eco-efficient Value Ratio	EEVR	The model of the EEVR is developed to analyse the required delinking of the economy and the ecology on a product level as well as on a system level: the EEVR is a single indicator for sustainability. The basic idea is to combine the 'value chain' of Porter with the ecological consequences this value chain has in terms of eco-costs. The idea is based on the fact that every step in the value chain adds costs, eco-costs and value to the total system: optimal sustainable design has the lowest Eco-costs/Value Ratio for the total system from cradle to grave. The EEVR model links the production side of the environmental problem (i.e. make products with lower eco-costs) to the consumer side (i.e. give environmentally sustainable products a higher relative value so that consumers will buy it). A product or service is considered to be "clean" when eco-costs are below a certain threshold: the market average is thought to be 0.4, so different estimates put a "clean" products between 0.04 and 0.1. Eco-costs: single indicator which can be calculated as the result of the LCA analysis Market value: value perceived by the customer, approximated by the price EEVR = Eco-costs / Value 
15	Resource Duration Indicator	RDI	A new performance metric, the longevity indicator, which measures contribution to material retention based on the amount of time a resource is kept in use. The measure is the sum of three generic components: initial lifetime (A), earned refurbished lifetime (B) and earned recycled lifetime (C)

16	Material Circularity Indicator	MCI	The MCI, developed by the EMF, combines aspects of lifetime and intensity of use with the proportion of recycled material and the share of materials in a product that can be recycled in a single indicator, applicable at the product or company level. It considers material rates of recycling and reuse, measures how restorative flows are maximized and linear flows are minimized, and also the length and intensity of the product's use. Constructed from a combination of three product characteristics: - the mass of virgin raw material used in manufacture - the mass of unrecoverable waste that is attributed to the product - utility factor that accounts for the length and intensity of the product's use There can be two approaches: - Whole product approach: the formula does not differentiate between the different components and materials of a product. - Comprehensive approach: adapts it to consider a breakdown of components and materials.
17	Potential Recycle Index	PRecI	Contains a potential recycle index that considers the fraction of recyclable mass in the product, number of components, the efficiency of the recycling process etc..
18	Combination Matrix	CM	Longevity: the sum of three components: the time for which a resource is first used (A); the time for which a resource is used due to product refurbishment (B), and due to recycling (C) Circularity: the number of times a resource is used in a product system, so the sum of 'initial use' (NA), 'refurbishment' (NB), 'recycling' (NC) combines circularity and longevity of a product, and considers the contribution made by product remanufacturing along with recycling. The contribution of remanufacturing is measured as the proportion of remanufactured products (circularity) and refurbished lifetime (longevity), where circularity is expressed as a number between one and infinity, and longevity is expressed in time. includes initial lifetime, refurbished lifetime and recycled lifetime to assess the overall lifetime of products and materials. CM combines a revised LI with a circularity metric, and thus consider the lifetime and circularity of resources, and distinguishes between short linear, short circular, long linear and long linear resource use.

			
19	Recycling Desirability Index	RecDI	Calculates how desirable it is to recycle a product by summing three parameters, which measure respectively the material security index of the product as the weighted average of the MSI of its materials, the technology readiness level of the product as the weighted average of the TRL of its components, and the ease of recycling
20	Material Reutilization Score	MRS	In the Cradle2Cradle certification framework represents a calculation that combines the fraction of recycled or rapidly renewable content in a product with the fraction of material in a product that is recyclable, biodegradable or compostable $\frac{\left[\begin{matrix}\%\ recycled\ or\ rapidly\ renewable\\ product\ content\end{matrix}\right] + 2\left[\begin{matrix}\%\ of\ product\ recyclable\\ or\ biodegradable/compostable\end{matrix}\right]}{3} \times 100$
21	Design Method for End-of-use Product Value Recovery	EPVR	end-of-use options (recycling, reuse, disposal) are compared based on the disassembly costs needed for each strategy followed by design improvements to reduce disassembly costs.
22	End-of-life Index	EOLI	Consists of EOL indices for modules, sub-assemblies and components of a product. These indices provide an indication of how the product will perform at EOL in relation to disposal, disassembly and recovery (i.e. recycling and remanufacturing), and are based on a calculation of the total cost of each EOL process.
23	Product Recovery Multi-criteria Decision Tool	PR-MCDT	Decision-making tool that allows to select EOL strategies (e.g. recycling, remanufacturing, reuse, repair etc.) according to relevant economic, environmental and social indicators.
24	Decision Support Tool for Remanufacturing	DSTR	It assesses whether remanufacturing is economically and environmentally feasible. This is done using 17 variables describing the main cost components and some operational parameters such as the remanufacturing yield.

25	Eco-efficient Value Creation Method	EEVC	It combines costs, market value (customer perceived value) and eco-costs (costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth (the 'no effect level')) to assess the potential of remanufacturing, both in terms of environmental impacts and in terms of attractiveness to customer. The indicator also presents a sustainable business strategy matrix to analyze the short- and long-term market prospects of products and/or services, based on the eco-costs and the quality/cost ratio. This method is part of the more comprehensive model of the Eco-costs/Value Ratio (EVR). 
26	Eco-cost/Value Ratio	ECVR	It is LCA based (ISO 14044, 2006). It considers how clean or dirty a product is, and expresses resource-efficiency in terms of the ratio between eco-costs and the value of a product. It analyses potential negative environmental effects of business initiatives on a system level, and to provide a theoretical approach to the design of sustainable business models by means of a three dimensional approach of costs, eco-costs and market value. Two methods are applied for analysis and design: Eco-efficient Value Creation (EVR benchmarking) and the Circular Transition Framework (describing stakeholder activities which are required for the transition towards sustainable business models).
27	Value-based Resource Efficiency Indicator	VRE	Provides a mass-based indicator of the resource-efficiency of products or processes, and focuses on the economic value of resources, as the authors acknowledge the general lack of information about the environmental and social impact. $$VRE = \frac{Y}{\sum_i W_i X_i}$$ Where Y = output value (= gross output - intermediate inputs) X = Resources W = Weights, ideally environmental and social impacts of resources; in practice material and energy prices represent quality and scarcity of resources

28	Typology for Quality Properties	TQP	Screening tool that assesses the inherent, designed and created quality properties of materials, components and products (MCP) and distingueshes them between avoidable and unavoidable, with the aim of improving the resource-efficiency of MCPs.
29	Ease of Disassembly Metric	eDiM	It calculates the disassembly time of a product, and thus provides insights into the time required for the different disassembly tasks for each component in the product. A straightforward calculation sheet is employed in eDiM to calculate the disassembly time given the sequence of actions and basic product information.
30	Effective Disassembly Time	EDT	Similar approach to eDiM. It calculates the disassembly time for disassembling a product to isolate the target component, which takes into consideration all components of the product, the disassembly depth, type of liaison, liaison corrective factor, and best disassembly sequence. The difference in respect to the standard disassembly time is that it takes into consideration the corrective factors to model the specificity of any analysed liaison.
31	Disassembly Effort Index	DEI	It considers the work and processes needed to disassemble a product, and provides a DEI score (%), which can then be used to calculate the disassembly cost and the disassembly return on investment.
32	Multi-Criteria Decision Analysis Combining Material Circularity Indicators and Lifecycle Based Indicators	MCDA-ML	A framework that addresses multiple dimensions of product circularity by combining material circularity indicators like MCI and MRS with lifecycle based indicators from LCAs. By combining these two types of indicators with different weighting sets, MCDA-ML enables a nuanced assessment of circular strategies.
33	Circular Design Guidelines	CDG	Presents 30 circular design guidelines within the five key CE principles of extending life span, disassembly, product reuse, components reuse, and material recycling. CDG evaluates product design based on (i) the margin of improvement and (ii) the relevance to the design guidelines, which enables a classification of circularity improvement potential.
34	Circular Economy Toolkit	CET	Online toolkit consisting of guidelines and a tool that can support companies in assessing their improvement potentials. The assessment tool includes 33 questions within seven categories, each containing 20 sub-points (each sub-point is presented as two opposites and an intermediary option). Companies can use the tool to attain an overview of improvement potential within these seven categories, based on their answers. These seven categories cover broadly CE principles of different RE-strategies (repair, reuse, remanufacture, recycle) as well as production, use and business models for CE, enabling a broad CE assessment.

35	Revenue from upgrade, repair and maintenance services	RURM	This indicator measures the total amount of income generated by the sale of goods/products and services related to the company's primary operations. Revenues shows liability of a business. To continue as an ongoing business, a company must generate sufficient revenue to cover its costs and earn a profit. REVprod = Number of products type p produced and sold * the unit sale price for product type p; and REVserv = Number of service type s provided * the unit sale price for service type s.
36	Revenues from reused/repurposed products	RRRP	This indicator measures the total amount of income generated by the sale of reused goods/products. Extend product's use cycles by offering reused products and goods for sale. REVreused = Number of reused/repurposed products type j sold * the unit sale price for reused product type j.
37	Revenues from remanufactured products	RRemP	This indicator measures the total amount of income generated by the sale of remanufactured goods/products. Extend product's use cycles by offering remanufactured products and goods for sale. REVremanuf = Number of remanufactured products type j sold * the unit sale price for remanufactured product type j.
38	Revenues from refurbished products	RRefP	This indicator measures the total amount of income generated by the sale of refurbished goods/products. Extend product's use cycles by offering refurbished products and goods for sale. REVrefurb = Number of remanufactured products type j sold * the unit sale price for remanufactured product type j.
39	Revenues from reusable and recyclable components	RRRC	This indicator measures the total amount of income generated by the sale of reusable and recyclable components and parts to a third party. Retain value of the materials contained in the product by selling more reusable and recyclable components to third parties. The revenues are sales from the four classes of components, such as good and poor quality reusable components and good and poor quality recyclable components. Good quality reusable components are components characterized by good physical appearance and performance. Poor quality reusable components are the components that are either physically blemished or functionally disabled but are good candidates for recycling. Good quality recyclable components are the components that are recyclable directly or after minimal recovery operations. Before stock piling in the inventory the components are subjected to operations such as shredding, crushing, and stamping to achieve space efficiency and to command higher selling price. Poor quality recyclable components are the components that have less recycle value. They are sold as is or sent to disposal.

40	Reuse benefit/cost ratio	ReuBCR	This indicator allows to compute the revenue of the reuse scenario (BRE). Economic values for different EoL scenarios are calculated using the benefit to cost ratio approach. This indicator shows how economically beneficial is to offer used goods. The benefit to cost ratio (BCR) must be greater than or equal to 1, i.e. B/C > 1, where B is the benefit and C is the cost of each alternative. Higher value means it is economically beneficial to offer used products for sale. The resale value of the product (Bresale). The costs (CRE) arise from collection costs (Ccollection), transportation costs (Ctrans) and refurbishing costs (Crefurb = may include inspection, cleaning, packaging, etc.) (if refurbishment is needed).
41	Recycling benefit/cost ratio	RecBCR	The revenue of the recycling scenario (BRC) is a function of the weight of the recovered material (Bweight) and the market value of the material (Bvalue). Economic values for different EoL scenarios are calculated using the benefit to cost ratio approach. This indicator shows how economically beneficial is to offer recycled materials for sale. The benefit to cost ratio (BCR) must be greater than or equal to 1, i.e. B/C > 1, where B is the benefit and C is the cost of each alternative. Higher value means it is economically beneficial to offer reused products for sale. The costs (CRC) arise from collection costs (Ccollection), transportation costs (Ctrans), separation costs (Cseparation) and shredding costs (Cshred).
42	Take back cost	TBC	This indicator measures the costs incurred by a company that are associated with a procedure of product take back option. Take back collection requires reverse logistic in place as well as requires involvement of product users. Take bake option for products holds producers financially responsible for handling and treating their products at end of life in order to be dis- and reassembled, remanufactured, reused, repurposed, etc. TB cost = number of products ordered to be taken back (Yi) and the cost of collecting each product of type i.
43	Total sorting cost	TSC	This indicator measures the total sorting cost, i.e. cost to sort materials/components for further recycling, recovery or disposal. Sorting is needed to separate valuable parts and materials for proper recycling or recovery. Sorting Cost = cost to sort a discarded product of type j (or material type m) * a quantity of accepted returns of product type j (or material of type m).
44	Total acquisition cost	TAC	This indicator measures the total acquisition cost. This can be seen as a take back cost, however associated with discarded products. In case of a non-established take back system, the products at the end of their life or broken products can be purchased from the user. Cost acquis = cost to acquire a discarded product (acquisition price) of type j (EUR/unit) by quantity of acquired returns of product type j.

45	Cost of non-destructive disassembly	CND	This indicator measures the cost of a unit of product disassembly. Non-destructive disassembly is the systematic process of removing parts from an assembly whilst ensuring that no damage occurs as a result of the process. This type of disassembly is focusing on items rather than materials. Disassembly is difficult to calculate as various factors can affect the result, such as; component complexity, fastening methods, part fragility, wear resistance, and ease of identification and handling. Higher cost indicates that product is compex or was not designed to be diassembled. When product is disassembled, some parts can be reused, remanufactured or recycled. In case the product can not be disassembled, it can be recycled completely (not desirable due to high value loss) or treated as waste and disposed CND is the cost of non-destructive disassembly (considered for the items that are reused or the items that are sent to storage) and is calculated as CND = number of items to be reused (Xij) and stored (Vij), the cost per hour (cnd) and the time of disassembling each item (dtj) - taken from calculation of indicator "Disassembly Time of each component".
46	Cost of destructive disassembly	CDD	This indicator measures the cost of a unit of product disassembly. Destructive disassembly involves separating materials for recycling. Destructive disassembly is focusing on materials rather than items. Disassembly is difficult to calculate as various factors can affect the result, such as component complexity, fastening methods, part fragility, wear resistance, and ease of identification and handling. Higher cost indicates that product is complex or was not designed to be diassembled. It can lead to valuable material losses CDD = number of items to be recycled (R) and disposed (D) * the cost per hour (cd) * the time of disassembling each item (ddtj); ddtj is taken from calculation of indicator "Disassembly Time of each component".
47	Cost of recycling	CRec	This indicator measures the recycling cost which is defined as the amount of money to invest to remove targeted parts and materials. When product is disassembled for recycling, the purpose is to remove targeted parts, that can be reused, remanufactured or recycled. In case the product can not be disassembled, it can be recycled completely (not desirable due to high value loss) or treated as waste and disposed.
48	Cost of remanufacturing	CRem	This indicator measures the costs of product remanufacturing consisting of the costs of disassembly, inspection, cleaning, remanufacturing and reassembly. Remanufacturing can be both profitable and less harmful to the environment than conventional manufacturing as it reduces waste amount sent to landfill and the levels of virgin material, energy and specialised labour used in production.

49	Cost of refurbishing	CRef	This indicator measures the costs of components refurbishment consisting of the costs of disassembly, inspection, cleaning, and reassembly. Refurbishing ensures that those re-usable components are as capable as new components. If the target component is in good condition at its EOL then a minor refurbishing cost would be incurred e.g. cleaning. In contrast, a failed target component will incur higher refurbishing costs such as repair, replacement, etc. and the likely cost to refurbish is according to component failure/degradation rate data.
50	Cost of transportation in reverse supply chain	CT-RSC	This indicator measures the cost of transportation in reverse supply chain. This cost depends on the total distances traveled in reverse supply chain (can include collection of products at the customer, delivery to the dissassembly/remanufacturing site to either another supplier or original manufacturer). Strive to decrease this rate as it can save costs, energy and gaseous emissions. Encourage/set up local business to provide repair, maintenance or other service to avoid transportation to the original manufacturer. Also, try to recycle discarded items (scraps, waste) internally. Cfuel collect = ([Transported distance (km) / fuel consumption (km/l)] X cost of fuel (EUR/litre)/ Total qty. of used products/parts/materials transported) x information sharing cost and ordering cost.
51	Cost of user education on use and post-use opportunities	CUE	This indicator measures the amount of money spent on user (consumer/customer) education to equip customers with the knowledge & skills needed to make the most out of its product or services at any stage of product or service operation and the end of life. User education aims at increasing user awareness of product or services and related aspects. It also improves the producer-seller-buyer-user relationship and help retaining customers in a long run. Ceduc user = Total amount of money spent on user education.
52	Cost of supplier education and training	CSE	This indicator measures the amount of money spent on suppliers education and training to equip/enrich suppliers with the knowledge & skills in relation to sustainability solutions and innovative projects. Supplier education aims at increasing suppliers awareness of sustainability and related aspects in the supply chain. It also improves the supply chain relationship and help retaining them in a long run. Ceduc suppl = Total amount of money spent on supplier education.
53	First technical wear-out life	FTcWOL	This indicator measures the first wear-out life of a new product, in years. This life depends on internal factors such as 'product failure' and 'physical degradation'. When units of the product become old or damaged, they begin to fail at an increasing rate. It is called the "wearout" period. Aim for designing robust and long lasting products and parts to avoid product's technical premature obsolescence. First wear-out life in years or time of durability of a whole product.

54	First technological wear-out life	FTlWOL	This indicator measures the period for which the product can be used without an upgrade, and is based on external factors, such as technology infrastructure changes and attractiveness compared with competing products (in contrast to internal factors as physical degradation and failure). Aim at designing products taking into account future trends and technology developments. Period which the product can be used without an upgrade.
55	Second wear-out life or reuse cycle	SWOL	This indicator measures the second wear-out life of a product, that was repaired, reconditioned, refurbished or remanufactured and sent for another use cycle. When units of the product become old or damaged, they begin to fail at an increasing rate. It is called the “wearout” period. Aim for designing robust and long lasting products and parts to avoid product's technical obsolescence. Second wear-out life in years OR lifetime or a remanufactured/refurbished product/lifetime of a new product of the same type
56	Maintainable period after sales	MPAS	This indicator measures the maintainable time of the product after sales. Maintainable service can be predictive, preventive maintenance or corrective maintenance as well a repair service. By increasing maintainable period for products, you build a long term relationship with customers and retailers.
57	Time for service provision	TSP	This indicator measures time for the product to be delivered to the service point, to be upgraded, repaired, or inspected, and then delivered back to the user. Decrease waiting time for the user by establishing local service points and by training servicemen. Sum of all time for the product to be delivered to the service point, to be upgraded, repaired, or inspected, and then delivered back to the user.
58	Existence of Manual with environmental instructions	EM	Manual with environmental instructions is a user guidance that contains environmental instructions on how the product should be treated during use and at the end-of-life. Making the manual available for the user is important to facilitate proper end-of-life scenario of products and increase user awareness of end-of-life options.
59	Take-back offering for products	TBO	This indicator measures the number of customers that are offered contracts for products with a take back option at the end of product's life or use cycle. Take bake option for products holds producers financially responsible for handling and treating their products at the end of life. ProdTB = (Number of contracts (or customers) for products offered with a take back option / Total number of products sold) * 100%.

60	Number of campaigns on responsible consumption	NCRC	Active engagement of customer in campaigns towards more responsible consumption can facilitate behavioral change and acceptance of radical products and solutions. Campaigns on responsible consumption aim at increasing user awareness of product or services and related aspects. It also improves the producer-seller-buyer-user relationship and help retaining customers in a long run.
61	Availability of customer support option	ACSO	Customer support can provide valuable information to the customer about proper product use (for example, upgrade options, availability of recycling or recovery center etc). Availability of customer support improves the producer-seller-buyer-user relationship and help retaining customers in a long run.
62	Number of joint sustainability-oriented initiatives	NJSOI	Joint initiatives in supply chain towards sustainability creates a robust knowledge sharing and commitment base. Higher value indicates a larger involvement and awareness of sustainability and circular economy across supply chain actors.
63	Energy consumption for disassembly	ECD	A product has to be partially disassembled so that its components can be reused, remanufactured, or refurbished. Recycling requires complete disassembly. Disassembly process requires energy consumption, measured by this indicator. Reducing the energy consumption in disassembly improves the disassembly performance of the product. When designing products, make sure to connect parts in a way that will enable easier disassembly. The energy consumption of destroying the connection of the part i (kWh)* the number of parts (n).
64	Packaging Material Summary	PMS	This indicator measures the number of each individual packaging material in packaging system format. This indicator helps to get an overview of all the packaging material used to package products in a company. Aim at reducing number of different types of material for packaging to ease separation process.
65	Product and Packaging Recyclability	PPR	This indicator measures the total recyclability of the product, including packaging. Higher value indicates a higher content of recyclable materials in products and packaging. Aim at designing products that are made of recyclable material. Mass of recyclable material in the product and its packaging/Total mass of product including packaging.
66	Product Biodegradable Packaging	PBP	This indicator measures the mass of biodegradable packaging to the total packaging per product manufactured. Higher value indicates a higher content of biodegradable materials in packaging. Aim at designing/using biodegradable packaging and facilitating proper treatment of the end of life. Biodegradable packaging normally does not contain any toxic material or substances.

67	Total packaging mass	TPM	This indicator measures the total packaging mass used to pack a product. Higher value can indicate excessive use of packaging, thus increasing amount of solid waste. Aim at reducing packaging.
68	Packaging mass fraction	PMF	This indicator measures the fraction of the packaging mass in the total mass of the products. Higher value can indicate excessive use of packaging, thus increasing amount of solid waste. Aim at reducing packaging. Mpack frac = Packaging mass (kg) / total mass of products (kg).
69	Mass Fraction of Reusable Packaging	MFeuRP	This indicator measures the total reusable packaging mass used to total packaging mass. Higher value indicates a higher fraction of reusable packaging, which, then managed appropriately, can be directly reused as packaging internally or externally.
70	Packaging Recyclability per Product	PRP	This indicator measures the amount of recyclable packaging per product manufactured. Higher value indicates a higher content of recyclable packaging. Aim at using packaging that is made of recyclable material.
71	Mass Fraction of Recycled Packaging	MFRecP	This indicator measures the total recycled packaging mass used to total packaging mass. Higher value indicates a better use of recycled material and minimization of virgin material use.
72	Reused Packaging Materials per Product	RPMP	This indicator measures the mass of packaging material reused per product. Higher value indicates better use of used packaging material in a product. Reusing packaging can save energy, material and reduce amount of solid waste generated.
73	Take back packaging from post use	TBPPostU	This indicator expresses the post use packaging mass/volume received from consumers/buyers of a product. Packaging later can be reprocessed on site. Higher value indicates company's responsible management of own packaging after sale.
74	Take back packaging from pre-use	TBPPreU	This indicator expresses the pre-use packaging mass/volume received from internal facilities. Parts and materials can be packed and transported internally between factories and facilities. Aim to recirculate packaging internally. Packaging can be also reprocessed on site. Higher value indicates company's responsible management of own packaging after sale.
75	Efficiency of packaging design	EPD	This indicator measures the efficiency of packaging design, through the number of units packaged together. Higher value indicates efficiency of packaging design. Aim to decrease the total mass of packaging.

76	Re-packaging	ReP	This indicator measures the number of times product is repacked throughout supply chain. Higher value may indicate an excessive packaging used throughout supply chain. Improving this measure can reduce material consumption during pre-manufacturing and manufacturing life cycle stages. Number of times product is repacked throughout supply chain.
77	Discarded Packaging Materials per Product	DPMP	This indicator measures the mass of packaging material discarded per product. This indicator can be measured for the users, i.e. the packaging they discard. Higher value indicates an inefficient way of packaging system on site. Aim to reduce this value by improving packaging design or by avoiding packaging at all.
78	Packaging Scrap	PS	This indicator measures the mass of packaging scrap per product manufactured. Higher number may indicate inefficient packaging process resulting in excessive generation of scrap (e.g. packaging can be trimmed to a specific shape which may result in scrap).
79	Packaging to Landfill	PL	This indicator measures the total mass of packaging used to landfill (i.e. packaging that is not reused or recycled). It can also be measured to the total packaging used, as a percentage. Aim to eliminate any material sent to landfill. Aim to reuse or recycle packaging.
80	Amount of reused materials	ARM	This indicator measures the amount of reused materials to the total material consumption in manufacturing. Aim to reuse more parts after reconditioning or remanufacturing, also in own products.
81	Amount of recycled defects	ARD	This indicator expresses the rate of recycled defective products to the total number of defective products. Aim to recycle more defective products.
82	Amount of recycled by-products	ARBP	This indicator measures the amount of recycled by-products to the total amount of by-products generated in manufacturing. Aim to recycle more by-products.
83	Amount of recycled scrap	ARS	This indicator measures the percentage of scrap recycled in the production process per product manufactured. Aim to increase the amount of scrap that is recycled internally in production. However, aim to reduce amount of scrap generated in production. Large amounts of scrap indicates inefficiency of manufacturing process.
84	Total Recyclable Material in Manufacturing	TRMM	This indicator measures the use of recyclable materials in manufacturing per period of time. Aim to utilize more recyclable materials in manufacturing.

85	Recycled Material Fraction	RMF	This indicator measures the recycled material use to the total mass input in the manufacturing system. It can also be measured as an absolute indicator, reflecting the amount of recycled materials used in a period of time, for instance. Aim to substitute virgin material by recycled material (whenever possible).
86	Auxiliary Materials recycled or reused	AMRR	This indicator measures the amount of auxiliary materials recycled or reused in the (production) process. Aim to increase the amount of recycled or reused auxiliary materials in production.
87	Diversity of Materials in Production	DMP	This indicator measures the number of different materials used in production process. A high diversity of materials utilized in the production process means complexity when connecting parts, difficulties in assembly and disassembly, and high demands of energy during manufacture.
88	Total Material Consumption	TMC	This indicator measures the absolute mass of material input to manufacture the product. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process. This indicator should always be used together with "energy consumption" indicator to get a full efficiency picture.
89	Specific Material Consumption	SMC	This indicator measures the mass of material input per production output. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process. Aim to decrease amount of materials (i.e. light weight design) used to manufacture a product or to substitute virgin material with recycled feedstock. This indicator should always be used together with "energy consumption" indicator to get a full efficiency picture.
90	Number of Different Materials	NDM	This indicator measures the number of different materials in the product. Decrease this number can facilitate the disassembly and recycling process.
91	Fraction of Renewable Raw Materials	FRRM	This indicator measures the renewable raw materials use to the total mass input in the operational system. Renewable raw material (RRM) is a material of plant, animal, or microbial biomass, which are based on the photosynthetic primary production and are used outside the food and feed area for material or energy production. Aim to substitute raw material with renewable type.
92	Sustainability-certified materials/substances in product	SCMSP	This indicator measures share of sustainability-certified materials/substances/ingredients in material use for product manufacturing. Higher value indicates larger share of sustainability-certified materials in products use. Sustainability-certified materials/products have a smaller environmental and social impact than a non-labelled product/material.
93	Recyclable and reusable materials used by service providers	RRMSP	This indicator measures the amount of recyclable and reusable materials used by service providers (also contracted). It can improve the environmental performance by selecting the most efficient provider of energy and raw materials to support product during its operation.

94	Product Hazardous Materials	PHM	This indicator measures the amount of hazardous materials used per product manufactured. Hazardous materials present risks to human health and to the environment. It includes inflammable, corrosive, reactive, toxic and pathogenic materials. Reduce hazardous/toxic material content in products. Toxic substances can disrupt extended use of material/product, limiting its use and cause environmental and health damage.
95	Fraction for Re-assembly	FRA	This indicator measures the volume/amount of all the parts that are designed to be destined to re-assembly to the overall volume/unit of the product. It is used to calculate the indicator "Recyclable Fraction". Re-assembly eases product remanufacture, refurbishment and ensures proper recycling. It can also positively influence solid waste amounts as less components will be disposed of by being retrieved and sent for remanufacture or refurbishment. λreass = (Sum of volumes of all the parts destined to re-assembly)/ total volume of the product OR (sum of number of all the parts r destined to re-assembly)/per product.
96	Fraction for Re-manufacturing	FRemM	This indicator measures the volume/amount of all the parts that are designed to be destined to remanufacturing to the overall volume/unit of the product. Increases amount of parts destined to remanufacture. Remanufacture often saves energy, material and emissions compared to a new component/product manufacture. It also helps reducing solid waste amount. λrem = (Sum of volumes of all the parts destined to remanufacturing)/ total volume of the product OR (sum of number of all the parts destined to remanufacturing)/per product .
97	Fraction of Recyclable Material	FRecM	This indicator measures the volume fraction/number of recyclable materials in a product to the overall volume of the product. Increase amount of material destined to recycling processes. Recycling of materials makes it possible to avoid waste by recycling material to be used in manufacturing or other applications (cascading). λmat = (Sum of volumes of all the parts destined for recycling)/ total volume of the product OR (sum of number of all the parts destined to recycling)/per product Weight of recyclable materials/Total weight of product x 100 %.

98	Input of virgin material	IVM	This indicator measures quantity of the inputs that are coming from virgin materials in relation to the rest of materials coming from recycled or reused materials and components. Lower value of this indicator signals that most a larger mass of virgin material was substituted by recycled material or/and reused components. The mass of virgin material (VM) for each sub-assembly, part, and/or material: V(x) = M(x) * (1 - FR(x) - FU(x)), where M(x)—Mass of a product x; FR(x)—Fraction of mass of a product's feedstock x from recycled sources; FU(x)—Fraction of mass of a product's feedstock x from reused sources.
99	Re-assembled Fraction	RAF	This indicator is related to the indicator "Fraction for Re-assembly" by an α factor, which represents the volume losses (or efficiency of re-assembly) involved in the re-assembly process with values lower than one. Ensure that all the parts destined to re-assembly are properly retrieved. Re-assembly eases product remanufacture, refurbishment and ensures proper recycling. It can also positively influence solid waste amounts as less components will be disposed of by being retrieved and sent for remanufacture or refurbishment. Freass = ((Sum of volumes of all the parts destined to re-assembly)/ total volume of the product) * α reass.
100	Re-manufactured Fraction	RemF	This indicator is related to the indicator "Fraction for Re-manufacturing" by an α factor, which represents the volume losses (or efficiency of remanufacturing) involved in the retrieval process with values lower than one. Ensure that all the parts destined to remanufacture are used again for manufacturing or assembly. Remanufacture often saves energy, material and emissions compared to a new component/product manufacture. It also helps reducing solid waste amount. Frem = ((Sum of volumes of all the parts destined to remanufacturing)/ total volume of the product) * αrem.
101	Recycled Material Fraction	RecF	This indicator is related to the indicator "Fraction of Recyclable Materials" by an α factor, which represents the volume losses involved in the retrieval process with values lower than one. Increase amount of material destined to recycling. Recycling of materials make it possible to avoid waste by recycling material to be used in manufacturing or other applications (cascading). Fmat = ((Sum of volumes of all the parts t destined to recycling/ total volume of the product) * αmat.
102	Fraction of Reused Components	ReuF	This indicator measures the number of reused components to the total number of components in the product. Components can come after reconditioning, remanufacturing or refurbishing of a used product. Components can either be reused on site or sent to suppliers for reuse. Increase the amount of components that are reused internally or externally. It helps avoiding excessive part production and reducing solid waste Number of reused components/total number of components of the product OR Total reused component weight/total product weight.

103	Replaced parts	RP	This indicator measures the percentage of replaced parts in a reusable/remanufacturable product. Lower value indicates that product can either be reused without any repair or with minor part replacement, hence minimizing the need for material and energy consumption. However even if the value is high, it is more energy and material wise to replace broken/worn parts then to manufacture a new product (in most cases). Percentage of replaced parts in the product.
104	Number of components	NC	This indicator expresses how easily products can be assembled, disassembled or recycled based on its number of components. Design products with fewer components to ease assembly and disassembly Number of components of the product.
105	Number of Tools for Disassembling	NTD	The duration of the disassembly process is often directly related to the types of joints between materials. The joints should be as simple and standard as possible, so that there is little need of dismantling tools. This indicator quantifies the number of tools required for disassembly to the total number of articulations of the product. Design products with fewer components to ease disassembly.
106	Number of different tools	NDTo	This indicator quantifies the number of different tools used in disassembly. Design products with fewer components to ease disassembly.
107	Number of Reversible Joints	NRJ	The time required to disassemble reversible joints, such as screws and bolts, is much less than required for welded joints, so that the latter are much more complicated to disassemble and break up. This indicator quantifies the number of reversible joints to the total number of joints of a product. Design products with fewer welded joints (if possible) to ease disassembly.
108	End-of-life scenario	EoLS	This indicator measures the percentage distribution of the whole product end-of-life, e.g., the materials contained in the waste streams for recycling, incineration and landfills. Get an overview of the effectiveness of components utilisation at the end of product's life. This overview can show whether the components are managed in the most effective way (i.e. the way they were designed for end of life).
109	Number of parts to be disassembled	NPD	This indicator measures the actual number of parts to be disassembled. Aim for lower value. Design products with fewer components/parts to ease disassembly.
110	Number of parts not theoretically required	NPNR	This indicator measures the difference between the total number of parts and theoretical minimum number of parts. Aim for lower value. Design products with fewer components/parts to ease disassembly. (Total number of parts) - (Theoretical minimum number of parts).
111	Number of disassembly tasks	NDTa	This indicator measures the total number of disassembly tasks. Aim for lower value. Design products with fewer components/parts to ease disassembly.

112	Tasks which don't result in direct removal of a part	TNR	This indicator quantifies the number of tasks which don't result in direct removal of a part. Aim for lower value. Design products with fewer components/parts to ease disassembly.
113	Tool manipulations	TM	This indicator quantifies the number of tool manipulations required in disassembly. Aim for lower value. Design products with fewer components/parts to ease disassembly.
114	Hand manipulations	HM	This indicator quantifies the number of hand manipulations required in disassembly. Aim for lower value. Design products with fewer components/parts to ease disassembly.
115	Assembly Design Efficiency	ADE	This measure shows how far the assembly efficiency is from the 100% in an ideal hypothetical design. The indicator compares a given design to a hypothetical design of the same product which consists of the theoretical minimum number of parts and where each part can be assembled with minimal effort. Aim for higher efficiency of assembly. 3 x (Theor. Minimum Number of Parts) / Actual Assembly Time
116	Structural Depth	SD	The disassembly performance is related to the structural depth between parts of a product. Lower value of this indicator signals about a potentially more efficient disasembly process at the end of use/life of a product/component. Design products with fewer connections between components and parts.
117	Preparation Time	PT	This indicator is used to estimate the disassembly time of each component of the product. It is used to calculate the indicator "Disassembly Time of Each component". Aim for lower value. Design products with fewer components to ease disassembly. Time for identifying joint elements (Tpb) + Time for searching and identifying tools(Tps) + Time for gripping tools(Tpg).
118	Movement time	MT	This indicator is used to estimate the disassembly time of each component of the product. It is used to calculate the indicator "Disassembly Time of Each component". Aim for lower value. Design products with fewer components to ease disassembly. Time for moving between joint elements(Tmd) + Time for redirecting toward the side of joint elements(Td).
119	Operation Time/Disassembly Time	OTDT	This indicator is used to estimate the disassembly time of each component of the product. It is used to calculate the indicator "Disassembly Time of Each component". Aim for lower value. Design products with fewer components to ease disassembly. Time for aligning between tool and joint element(Tdal) + Time for tool operation area(Tda) + Time for basic separation of joint element(Tdb) + Time for intensity of work(Tw).

120	Post-processing time	PPT	This indicator is used to estimate the disassembly time of each component of the product. It is used to calculate the indicator "Disassembly Time of Each component". Aim for lower value. Design products with fewer components to ease disassembly. Time for post-processing due to weight and size of the disassembled parts (Tprsw) + Time for post-processing due to movement of disassembled parts (Tprdt) + Time for post-processing due to hazard (Tprd).
121	Disassembly Time of each component	DTC	This indicator is measured by the sum of the indicators "Preparation time", "Movement time", "Operation time" and "Post-processing time". Aim for lower value. Design products with fewer components to ease disassembly. Preparation time (Tp) + Movement time (Tm) + Operation time (Td) + Post-processing time (Tpr).
122	Disassembly time of the product	DTP	This measure of the disassembly time of the product is the sum of the disassembly time of each component, indicator "Disassembly Time of Each component". Aim for lower value. Design products with fewer components to ease disassembly. Sum of the disassembly time of each component of the product.
123	Same Material Joints	SMJ	This indicator measures the number of articulated parts that can be recycled together to the total number of joints of a product. If the joints are made from the same material or materials that are compatible for recycling, there is no need for separate pieces before recycling, reducing the time of disassembly. Therefore, higher number of same material joints will ease disassembly and recycling.
124	Number of types of fastener	NTF	This indicator measures the total number of different types of fastener in the product. Fasteners simplify assembly and re-assembly as they create simple non-permanent joints. Lower number of different type of fasteners can ease disassembly and reassembly.
125	Total number of fasteners	TNF	This indicator measures the total number of fasteners in the product. Lower number of fasteners can ease disassembly and reassembly.
126	Active functions	AF	This indicator measures the number of active functions in the product. More active functions signals about multifunctionality of the product. More active functions indicate about increased product functionality. Increased functionality can result in more active product use and substitute another products with fewer functionalities.
127	Number of modules	NM	This indicator measures the number of modules of the product. Modular design facilitates repair, reuse, recycling and remanufacture. However there is no ideal number of modules, it depends on sector and application.

128	Laminated or Compound Materials	LCM	This indicator measures the mass of laminated materials or compounds in relation to the total weight of the product. Laminated or compound materials have limited potential for recycling.
129	Painted, Stained or Pigmented Surfaces	PSPS	This indicator measures the sum of the painted, pigmented or stained surfaces to the total surface of the product. The presence of painted, stained or pigmented surfaces problems often affect recycling processes, since these impregnations or alterations of the components complicate the separation for recycling due to the difficulty of separating the paint coats from the underlying materials.
130	Material identification labels	MIL	This indicator measures the percentage of product parts that carry material identification labels. One of the important aspects in the disassembly and subsequent recycling is identify which materials the product is made of.
131	Labeling of material types	LMT	This indicator measures the number of different materials identified in the product, in order to facilitate collection and recycling. One of the important aspects in the disassembly and subsequent recycling is identify which materials the product is made of.
132	Intelligent Materials	IM	This indicator measures the weight of "intelligent materials" to the total weight of the product. "Intelligent materials" are materials which undergo reversible physical or chemical changes under variations of magnetic or electrical fields, and they are capable of repeating this process indefinitely without losing their original properties. The use of intelligent polymers and metals is very important to reduce the disassembly time.
133	Recycled glass usage	RGU	This indicator measures the recycled glass usage as percentage of total glass weight in the product. Aim to increase substitution of virgin glass by recycled glass (whenever possible). Recycled glass usage in the product/Glass usage in the product * 100%
134	Recycled plastics usage	RPlU	This indicator measures the recycled plastics usage as percentage of total plastic weight in the product. Aim to increase substitution of virgin plastic by recycled plastic (whenever possible). Recycled plastics usage in the product/Plastics usage in the product * 100%
135	Recycled paper usage	RPaU	This indicator measures the recycled paper usage as percentage of total paper weight in the product. Aim to increase substitution of paper by recycled paper (whenever possible). Recycled paper usage in the product/Paper usage in the product * 100%
136	Recycled Containerboard usage	RCU	This indicator measures the percentage of recycled containerboard used in the product, including the containerboard packaging weights. Aim to increase substitution of containerboard by recycled containerboard (whenever possible). (Weight of recycled containerboard/Weight of all containerboard used in the product, including packaging) * 100%

137	Recycled Embodied Energy	REE	The Recycled Embodied Energy indicator is defined as the energy necessary to recycle and produce one kg of the recycled material of type m. Investigate the EE index of raw materials that are used in your product. Choose materials with lower EE index. Moreover, usually the energy necessary for recycling of the materials is less than the energy used for primary production, therefore try to select recycled materials as your feedstock material in a product. Energy necessary to recycle and produce one kg of the recycled material type
138	Recycling Efficiency	RE	Quantifies how efficient the recycling processes used to produce recycled input and to recycle material after use are. This indicator in itself is a circularity indicator. Some materials require much less energy to be recycled compared to the original manufacturing. However recycling may not be beneficial energy wise for all the materials. The values of efficiency of the recycling process for a specific material and recycling process will depend on a wide range of factors such as: material(s)—some materials are easier to recycle and will often have higher recycling efficiency; the quantity of material(s) involved; the recycling preparation process—higher efficiency can be expected when product disassembly takes place prior to material recovery; Values for recycling efficiency can be derived from various sources, for example: Reference Documents on Best Available Techniques from the European IPPC Bureau;
139	Additional material to create recycled feedstock	AMRF	This indicator measures the amount of additional material (material can be waste or leftover material) needed to create recycled feedstock to be used for product manufacture. Amount of additional material indicates how much more material would be needed to produce a desired recycled amount accouting for inefficiencies of recycling process. Importance of the value of this indicator depends. For example, by increasing the fraction of recycled feedstock to be used in a product, more material is required. However, this material can come from waste collected and recycled (for example, plastic waste collected from oceans; waste mined from landfills) Ec (efficiency of the recycling process used for recycling the product at the end of its use phase) = Ef (the recycling process to produce recycled content to be used as feedstock is about material leaving the recycling process) only in a closed loop processes
140	Waste converted to Reusable Material	WCRM	This indicator measures the amount of waste generated by the production process converted to reusable material per year. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process and a waste sorting process. Higher number indicates better management of internal waste and recovery of valuable material that can be reused on site.

141	Spare Parts and Consumables	SPC	This indicator measures the total number of spare parts and consumables of the product. Spare parts and consumables are parts of the product that wear out and need regular replacement. Higher number of such may indicate the need to re-design a product and parts, to extend the product's use cycle without the need of repair or maintenance. Number of spare parts and consumables.
142	Product Solid Waste Fraction	PSWF	In this approach, the product is treated as solid waste if there is no EoL management option other than landfilling or incineration available. Higher number may indicate that there is no established take back system allowing collection of the product to be reused, remanufactured or recycled. Mass of non-recovered parts of the product/Total mass of product.
143	Waste generated in the recycling process	WGRP	This indicator measures the waste amount generated in the recycling process. Important: the recycling process is a process used to recycle the product after collection (so it is about material entering the recycling process for recycling). Importance of the value of this indicator depends. For example, the value can be low due to smaller fraction of the product being collected for recycling, hence generating less waste from recycling process, however, it may also indicate that the rest of the fraction of the product is destined to landfiling (in better cases the rest was retrieved for reuse and remanufacture). Ec (efficiency of the recycling process used for recycling the product at the end of its use phase) = Ef (the recycling process to produce recycled content to be used as feedstock is about material leaving the recycling process) only in a closed loop processes
144	Rate of Defective Products	RDP	This indicator measures the number of defective products to the number of manufactured products. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process. Aim to decrease amount of defects. Decrease this rate to reduce solid waste generation, and wasted materials and energy. Number of defective products / total number of manufactured products
145	Landfill Waste per Product	LWP	This indicator measures the quantity of material sent to landfill per unit of product. Aim to eliminate materials sent to landfill. Quantity of material sent to landfill per unit of product.
146	Recycled Solid Waste Mass Fraction	RSWMF	This indicator measures the recycled solid waste mass to the total amount of solid waste generated. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process and a waste sorting process. Higher number indicates efficient management of internal waste and recovery of valuable material that can be reused on site. Recycled solid waste mass/Total mass of solid waste generated
147	Total Solid Waste Mass for Disposal	TSWMD	This indicator measures the solid waste mass generated for disposal, and can also be measured in a certain period of time. Measuring this indicator gives a good understanding of the efficiency of the manufacturing process and a waste sorting process. Higher number indicates inefficient management of internal waste.

148	Hazardous Solid Waste Mass Fraction	HSWMF	This indicator measures the relative quantity of hazardous solid waste produced by the company to the total amount of waste generated. Higher number may indicate inefficient use of hazardous/toxic material in production resulting in high amount of waste. Hazardous wastes pose a greater risk to the environment and human health than non-hazardous waste.
149	Hazardous Solid Waste Mass	HSWM	This indicator measures the total amount of hazardous solid waste produced by the company. Higher number may indicate inefficient use of hazardous/toxic material in production resulting in high amount of waste. Hazardous wastes pose a greater risk to the environment and human health than non-hazardous waste.
150	Linear Flow Index for Product Families	LFI2	Measures the proportion of material flowing linearly, that is, from virgin materials and up to unrecoverable waste. LFI2 is calculated as the sum of the relation obtained by dividing the amount of the product family material flowing in a linear fashion by the sum of amounts of product family material flowing in a linear and a restorative fashion
			$LFI2 = \sum_{j=1}^{n} \frac{V+W}{2M_t + \frac{W_{fj}-W_{cj}}{2}}$ where Vj is defined as the mass of virgin feedstock used to manufacture a j product variant. Wj is the mass of unrecoverable waste associated with a j product variant manufacturing, Mj is the total mass of the product variant, Wfj is the mass of unrecoverable waste generated when producing recycled feedstock for the j product variant, and Wcj is the mass of unrecoverable waste generated in the process of recycling parts for the j product variant
151	Potential Reuse Index	PReuI	The measurement of the degree of potential reuse of components between different product variants within the product family
			$Potential\ Reuse\ Index = \frac{\sum_{i=1}^{n} M_{ri} * k_i}{M_t}$ where Mri is defined as the mass of reusable component i, ki is the number of times the component is reused in the product family from product variant 1 to product variant n, and Mt is the total mass of the product family
152	Sustainable Circular Index	SCI	A synthesis of multiple sustainable and circular indicators built using the following steps: Phase 1—Selection of sustainability (social, environmental and economic) and circularity indicators (considering the procurement, use and disposal phases) Phase 2—Weighting of indicators, through weights proposed by expert judgement in a Delphi assessment Phase 3—Normalization Phase 4—Aggregation method for Index construction (through Simple Additive Weighting) Phase 5—Index construction

B Appendix B

#	Acronym	Strategy (10R)	BSC Perspective	Min Maturity Level	Type	Source
1	RRs	Recycle	Internal business process		Indicator	https://onlinelibrary.wiley.com/doi/10.1111/jiec.12506/abstract
2	EoL-RRs	Recycle	Internal business process		Indicator	https://digitalcommons.unl.edu/usgsstaffpub/596
3	CEPI	Recycle	Internal business process		Indicator	https://www.sciencedirect.com/science/article/pii/S0921344917300241
4	RPI	Reuse	Internal business process		Indicator	https://www.ncbi.nlm.nih.gov/pubmed/24594758
5	RIs	Recycle	Internal business process		Indicator	https://www.researchgate.net/publication/303936442_Recycling_indices_visualizing_the_performance_of_the_circular_economy
6	CEIP	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Internal business process	Integrative	Questionnaire	https://www.tandfonline.com/doi/abs/10.1080/19397038.2017.1333543
7	CPI	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, Recover	Internal business process, Leaning and growth, Supply Chain	Integrative	Questionnaire	https://www.designsociety.org/publication/39507/hybrid_top-down_and_bottom-up_framework_to_measure_products_circularity_performance

8	PLCM	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle	Financial		Indicator	https://onlinelibrary.wiley.com/doi/10.1111/jiec.12552/abstract;jsessionid=059DB5EE5821F8C8B7191E4650BB83D2.f03t04
9	CEI	Recycle	Financial		Indicator	https://dx.doi.org/10.4236/jep.2015.610096
10	CI	Recycle	Internal Business Process		Indicator	https://onlinelibrary.wiley.com/doi/10.1111/jiec.12599/abstract
11	CLC	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Internal Business Process		Questionnaire	https://www.kingfisher.com/content/dam/kingfisher/Corporate/Documents/Sustainability/Reports_publications/2013/kingfisher_closed_loop_innovation.pdf
12	CP	Refuse, Rethink, Reduce	Learning and Growth		Questionnaire	https://rescomd58.eurostep.com/idealco/pathfinder/
13	IOBS	Reduce, Rethink, Refuse, Recycle	Learning and Growth		Method	https://www.sciencedirect.com/science/article/abs/pii/S0959652618330221
14	EEVR	Refuse, Rethink, Reduce	Financial, Sustainability	Integrative	Indicator	https://www.sciencedirect.com/science/article/pii/S0959652615006332#fig2
15	RDI	Reuse, Refurbish, Recycle	Internal Business Process	Integrative	Indicator	https://www.sciencedirect.com/science/article/pii/S0959652616304784
16	MCI	Reuse, Recycle, Recover	Internal Business Process	Integrative	Indicator	https://ellenmacarthurfoundation.org/material-circularity-indicator
17	PRecI	Recycle	Internal Business Process		Indicator	https://doi.org/10.1016/j.jclepro.2018.06.131
18	CM	Reuse, Recycle, Refurbish, Remanufacture	Internal Business Process	Integrative	Matrix	https://doi.org/10.1016/j.ecolecon.2018.04.030
19	RecDI	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/pii/S09

						59652617306686?via%3Dihub
20	MRS	Recycle, Recover	Internal Business Process		Indicator	https://api.c2ccertified.org/assets/std_c2ccertified_productstandard_v3.1_030220.pdf
21	EPVR	Rethink, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Internal Business Process	Explorative	Method	https://doi.org/10.1115/1.4041574
22	EOLI	Remanufacture, Recycle, Recover	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/pii/S0959652613007609?via%3Dihub
23	PR-MCDT	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Learning and Growth		Method	https://doi.org/10.1007/s13243-018-0064-8
24	DSTR	Remanufacture	Internal Business Process		Method	https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1367107
25	EEVC	Remanufacture	Learning and Growth, Sustainability		Method	https://link.springer.com/article/10.1007/s13243-017-0031-9
26	ECVR	Refuse, Rethink, Reduce	Sustainability, Supply Chain	Integrative	Method	https://www.sciencedirect.com/science/article/pii/S0959652615006332?via%3Dihub
27	VRE	Refuse, Rethink, Reduce	Sustainability, Financial		Indicator	https://www.sciencedirect.com/science/article/pii/S0921344917300447?via%3Dihub
28	TQP	Refuse, Rethink, Reduce	Internal Business Process		Method	https://doi.org/10.1016/j.scitotenv.2018.07.344
29	eDiM	Refuse, Rethink, Reduce	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/pii/S0921344917301763?via%3Dihub

30	EDT	Refuse, Rethink, Reduce	Internal Business Process		Indicator	https://link.springer.com/article/10.1007/s00170-017-1201-5
31	DEI	Refuse, Rethink, Reduce	Internal Business Process		Indicator	https://www.tandfonline.com/doi/abs/10.1080/002075400189356
32	MCDA-ML	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Internal Business Process, Sustainability, Learning and Growth	Integrative	Method	https://www.sciencedirect.com/science/article/pii/S0921344918303677?via%3Dihub
33	CDG	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Internal Business Process, Learning and Growth		Method	https://doi.org/10.1016/j.jenvman.2018.08.014
34	CET	Refuse, Rethink, Reduce, Reuse, Repair, Remanufacture, Recycle	Internal Business Process, Learning and Growth		Method	https://circulareconomytoolkit.org/Assessmenttool.html
35	RURM	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
36	RRRP	Reuse, Repurpose	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
37	RRemP	Remanufacture	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
38	RRefP	Refurbish	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
39	RRRC	Reuse, Refurbish, Remanufacture, Recycle	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
40	ReuBCR	Reuse, Refurbish, Repurpose	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

41	RecBC R	Recycle	Internal Business Process, Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
42	TBC	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Financial, Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
43	TSC	Recycle, Recover	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
44	TAC	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
45	CND	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
46	CDD	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
47	CRec	Recycle	Internal Business Process, Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
48	CRem	Remanufacture	Internal Business Process, Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
49	CRef	Refurbish	Internal Business Process, Financial		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
50	CT-RSC	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Supply Chain, Financial	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
51	CUE	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Customer Relationship, Supply Chain		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

52	CSE	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
53	FTcWOL	Reduce, Rethink, Refuse	Internal Business Process, Customer Relationship	Basic	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
54	FTlWOL	Reduce, Rethink, Refuse	Customer Relationship		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
55	SWOL	Reduce, Rethink, Refuse, Reuse, Repair, Refurbish, Remanufacture, Repurpose	Internal Business Process, Customer Relationship	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
56	MPAS	Repair	Customer Relationship, Supply Chain		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
57	TSP	Reuse, Repair, Refurbish, Remanufacture, Repurpose	Customer Relationship, Supply Chain, Internal Business Process	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
58	EM	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Customer Relationship	Explorative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
59	TBO	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Customer Relationship, Supply Chain	Explorative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
60	NCRC	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Customer Relationship, Supply Chain, Sustainability	Regenerative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

61	ACSO	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Customer Relationship, Supply Chain		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
62	NJSOI	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Supply Chain, Sustainability	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
63	ECD	Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
64	PMS	Refuse, Rethink, Reduce, Recycle, Recover	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
65	PPR	Refuse, Rethink, Reduce, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
66	PBP	Refuse, Rethink, Reduce, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
67	TPM	Refuse, Rethink, Reduce	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
68	PMF	Refuse, Rethink, Reduce	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
69	MFeuRP	Reuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
70	PRP	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
71	MFRecP	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
72	RPMP	Reuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

73	TBPPostU	Reuse, Repair, Recycle	Internal Business Process, Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
74	TBPPreU	Reuse, Repair, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
75	EPD	Reduce, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
76	ReP	Reduce, Refuse	Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
77	DPMP	Reduce, Refuse, Rethink	Internal Business Process, Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
78	PS	Reduce, Refuse, Rethink	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
79	PL	Reuse, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
80	ARM	Reuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
81	ARD	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
82	ARBP	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
83	ARS	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
84	TRMM	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
85	RMF	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

86	AMRR	Reuse, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
87	DMP	Reduce, Rethink, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
88	TMC	Reduce, Rethink, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
89	SMC	Reduce, Rethink, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
90	NDM	Reduce, Rethink, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
91	FRRM	Rethink, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
92	SCMSP	Rethink	Sustainability, Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
93	RRMSP	Reduce, Reuse, Recycle	Sustainability, Supply Chain	Integrative	Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
94	PHM	Reduce, Rethink, Refuse	Sustainability, Internal Business Process, Customer Relationship		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
95	FRA	Refurbish, Remanufacture, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
96	FRem M	Remanufacture	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
97	FRecM	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
98	IVM	Reduce, Refuse, Reuse, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

99	RAF	Refurbish, Remanufacture, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
100	RemF	Remanufacture	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
101	RecF	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
102	ReuF	Reuse, Refurbish, Remanufacture	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
103	RP	Repair, Reuse, Remanufacture, Refurbish	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
104	NC	Refurbish, Remanufacture, Repair, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
105	NTD	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
106	NDTo	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
107	NRJ	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
108	EoLS	Recycle, Recover	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
109	NPD	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

110	NPNR	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
111	NDTa	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
112	TNR	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
113	TM	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
114	HM	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
115	ADE	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
116	SD	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
117	PT	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
118	MT	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

119	OTDT	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
120	PPT	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
121	DTC	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
122	DTP	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
123	SMJ	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
124	NTF	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
125	TNF	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
126	AF	Reduce, Rethink, Refuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
127	NM	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
128	LCM	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

129	PSPS	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
130	MIL	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
131	LMT	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
132	IM	Refurbish, Remanufacture, Repair, Repurpose, Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
133	RGU	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
134	RPlU	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
135	RPaU	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
136	RCU	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
137	REE	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
138	RE	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
139	AMRF	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
140	WCRM	Reuse	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889

141	SPC	Repair	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
142	PSWF	Recycle, Recover	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
143	WGRP	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
144	RDP	Reduce	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
145	LWP	Recycle, Recover	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
146	RSWMF	Recycle	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
147	TSWMD	Reduce	Internal Business Process		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
148	HSWMF	Reduce	Internal Business Process, Sustainability, Customer Relationship		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
149	HSWM	Reduce	Internal Business Process, Sustainability, Customer Relationship		Indicator	https://www.sciencedirect.com/science/article/abs/pii/S0959652619331889
150	LFI2	Recycle, Recover	Internal Business Process		Indicator	https://doi.org/10.1016/j.jclepro.2018.06.131
151	PReuI	Reuse	Internal Business Process		Indicator	https://doi.org/10.1016/j.jclepro.2018.06.131

152	SCI	Reduce, Rethink, Refuse, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recover, Recycle	Internal Business Process, Sustainability	Systematic	Method	https://www.mdpi.com/2079-9276/6/4/63

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