Understanding the dimensions, factors, and mechanisms of potential rebound effects in circular manufacturing: development of a detection-driven tool

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MECHANICAL AND MANAGEMENT ENGINEERING
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Final Dissertation

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Abstract

The transition to a circular economy (CE) is increasingly promoted as a pathway to reduce resource use, environmental impacts, and dependence on virgin materials. However, circular strategies, widely applied in manufacturing, may unintentionally trigger rebound effects (REs). REs occur when sustainability-oriented actions, such as those related to circular strategies, generate systemic responses that partially or fully offset their intended environmental benefits. Through mechanisms such as increased production, consumption, or resource use, well-intentioned interventions may therefore undermine sustainability goals. Despite growing academic interest, REs in circular manufacturing remain conceptually fragmented, underexplored at the industrial level, and largely unsupported by practical tools. This thesis addresses these gaps by developing a tool to support companies in detecting potential REs that may arise during the implementation of circular strategies in manufacturing.

The research adopts the Design Research Methodology and follows four stages. First, a systematic literature review identifies five key CE–RE dimensions (i.e., Business model, Drivers, Circular manufacturing ecosystem, Product lifecycle management, and Socio-economic aspects) and analyses how different types of REs may emerge across them. The results are synthesised in conceptual maps that structure the relationships between circular initiatives and rebound dynamics. The rebound mechanisms—defined as qualitative causal connections between interdependent elements that lead to specific effects—are used to explain how circular strategies may inadvertently trigger REs across business processes. Second, based on the conceptual maps, a CE–RE reference model is developed to capture the causal pathways through which circular initiatives propagate across different levels of analysis. Third, these insights inform the construction of an impact model that describes how circular solutions may lead to REs and identifies where a support tool can intervene. Building on this model, a detection-driven tool is developed to operationalise rebound mechanisms through a structured qualitative questionnaire, mechanism-based logic, and links to performance indicators aligned with CE strategies and sustainability goals. Finally, expert interviews are used to provide an initial validation of the tool, offering feedback on its clarity, usability, and practical relevance.

The findings show that REs arise not only from efficiency improvements but also from behavioural responses, market dynamics, technological optimisation, and organisational decisions. The thesis contributes to theory by systematising and expanding knowledge across CE–RE dimensions, clarifying causal mechanisms, and integrating producer- and consumer-related rebound pathways into a unified analytical framework. It contributes to practice by raising awareness of the potential occurrence of unintended effects during the implementation of CE strategies and by offering a structured approach to anticipating such consequences, supporting decision-making, and guiding the selection of performance indicators for early RE monitoring. Policy-relevant insights further highlight the need for regulatory instruments that explicitly address rebound risks within CE initiatives.

A key limitation of this research is that the detection-driven tool has not been rigorously tested through full industrial applications beyond expert consultations. Future research should therefore focus on empirical validation through case studies, pilot tests, and field experiments to assess usability, refine mechanism definitions, and evaluate the tool's ability to support decision-making in real operational contexts.

Overall, this thesis advances the understanding of REs in circular manufacturing and provides a foundational, methodologically robust, and practitioner-oriented framework for detecting and managing potential unintended consequences in the transition towards a CE.

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List of abbreviations

Abbreviations	Meaning
AHP	Analytic Hierarchy Process
B2B	Business to Business
BoL	Beginning of life
CE	Circular Economy
DEA	Data Envelopment Analysis
DES	Discrete Event Simulation
DfX	Design for X
DRM	Design research methodology
Em	Emergy
EoL	End of life
Ex	Exergy
I-O	Input-output
KPI	Key performance indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MCDM	Multi-Criteria Decision Making
MFA	Material Flow Analysis
MICRON	MIcro CirculaR ecOnomy iNdex
MoL	Middle of life
PLM	Product lifecycle management
PSS	Product-service system
RE	Rebound effect
SBToolPT	Sustainability Assessment Tool
SDGs	Sustainable Development Goals
TBL	Triple Bottom Line
WEEE	Waste from Electrical and Electronic Equipment

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1. Introduction

Humanity is currently confronting unprecedented environmental pressures, with six planetary boundaries—including climate change and biodiversity loss—already being transgressed (Richardson et al., 2023). These accelerating disruptions are driven by long-standing global megatrends such as population growth, rapid urbanisation, and large-scale migration, all of which intensify resource consumption and pollution. Combined with unsustainable production patterns and a culture of excessive consumerism, these dynamics are contributing to the depletion of finite natural resources, ecosystem degradation, and severe environmental pollution (Acerbi and Taisch, 2020; Sassanelli et al., 2023b).
Within this context, the manufacturing industry plays a central and paradoxical role. On one hand, it is essential to global prosperity: around 70% of world trade is linked to industrial activities, and approximately 60% of employment occurs in this sector (WMF Foundation, 2019). Manufacturing contributes roughly 16.6% to global GDP (Ritchie et al., 2020; Roser et al., 2023), making it a cornerstone of economic development. On the other hand, it is a major driver of environmental degradation. Manufacturing activities account for nearly 57% of global greenhouse gas emissions (Zacharia, 2025), and in Europe alone they are responsible for more than half of total global greenhouse gas emissions, largely due to energy-intensive processes (Karakosta, 2016). Globally, annual CO_2 emissions continue to rise—by 1.1% between 2022 and 2023—paralleling continuous population growth of around 0.88% per year ("Global CO2 emissions by year 1940-2023," 2023; "World Population by Year," 2024). The European Environment Agency estimates that air pollution from Europe's largest industrial plants generates annual economic losses between €268 and €428 billion—equivalent to about 2% of the European Unions' gross domestic product (European Environment Agency, 2025). Meanwhile, global waste generation is projected to exceed 3.8 billion tonnes per year by 2050 (Masterson, 2024).

Altogether, these trends highlight the urgency of transforming current production and consumption models. In response, governments, industries, and researchers have intensified efforts to foster sustainability and address the root causes of environmental decline (Mauser et al., 2013). A central pillar in this global transition is the circular economy (CE), which seeks to decouple economic growth from resource consumption by shifting from the traditional linear "take–make–dispose" paradigm to regenerative systems in which resources remain in productive loops for as long as possible (Gregson et al., 2015). CE principles—reducing, reusing, remaking, and recycling—aim to narrow, slow, and close resource loops (Gregson et al., 2015), delivering benefits such as reduced energy and material use, lower greenhouse gas emissions, and decreased reliance on virgin resources (Rosa et al., 2019a).

Manufacturing is central to this transition, as a resource-intensive sector, and has increasingly embraced circular strategies to improve productivity, extend product value, minimise waste and environmental impacts (Gusmerotti et al., 2019). These efforts, commonly referred to as circular manufacturing, include circular design, servitisation, cleaner production, remanufacturing, recycling, and advanced waste management—strategies that require coordination across multiple actors, technologies, and information flows (Acerbi et al., 2022). Companies are increasingly assessing their maturity in adopting these practices, although existing maturity models remain largely qualitative, signalling the need for more measurable and systemic approaches (Acerbi et al., 2024).

From a theoretical standpoint, this study is situated at the intersection of research on CE implementation in manufacturing systems and sustainable production systems engineering. It builds on work addressing circular business model innovation, circular manufacturing strategies, such as remanufacturing, servitisation, and closed-loop production, and the development of frameworks for evaluating circularity performance and maturity. At the same time, it is grounded in the broader literature on technological development and industrial transformation, which examines how digitalisation, advanced manufacturing technologies, and system-level coordination shape and influence sustainability transitions within industrial ecosystems.

The global importance of CE is reflected in major policy frameworks. The United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (“Affordable and Clean Energy”) and SDG 12 (“Responsible Consumption and Production”), are directly aligned with circular principles, reinforcing the need for resource efficiency and sustainable industrial practices (United Nations, 2015). More broadly, the SDGs reinforce the need for integrated economic, environmental, and social action—an approach inherently embedded in the CE paradigm.

In response to these global objectives, governments have introduced specific policy instruments to support CE adoption.

In Europe, the European Green Deal and the Circular Economy Action Plan promote sustainable production and consumption, regulate green claims to prevent greenwashing, strengthen recycling practices, and establish stricter rules for managing waste electrical and electronic equipment (WEEE) (European Union, 2021). The Eco-design for Sustainable Products Regulation expands design criteria to durability, repairability, and recyclability, while the Waste Framework and Right to Repair Directive promote waste prevention and extended product lifetimes (European Commission, 2024). A pivotal component is the Digital Product Passport, which ensures data transparency on product composition, origin, repairability, and recyclability across value chains (HaDEA, 2023). Complementarily, the ISO 59000 family—especially ISO 59020:2024—provides unified guidelines, indicators, and reporting standards for assessing circularity performance (ISO, 2024a, 2024b).

These initiatives have encouraged many European Union countries to implement new circular production and consumption models aimed at reducing raw material use and alleviating environmental pressures across key sectors, including manufacturing (Geerken Shahrzad Manoochehri and Di Francesco, 2022).

Within the literature on CE transitions in manufacturing systems, increasing attention has been devoted to the systemic consequences of CE implementation. Despite the substantial environmental benefits promised by the CE, its implementation is not free from challenges. Transitioning to circular business models, supply chains, and ecosystems introduces organisational, behavioural, and technological complexities that may generate unintended counter-effects, potentially undermining the anticipated gains (Sassanelli et al., 2023). Among these challenges, one of the most critical is the rebound effect (RE)—a phenomenon in which actions intended to enhance

sustainability may inadvertently trigger increases in resource use, emissions, or consumption, thereby offsetting some or all of the expected benefits (Lange et al., 2021).
The origins of the RE trace back to 19th-century energy economics, when Jevons (1866) observed that improvements in coal-use efficiency paradoxically led to higher overall consumption, later termed the "Jevons Paradox." This insight shaped modern definitions of REs as situations where efficiency improvements reduce costs, stimulate additional demand, and diminish the net environmental benefits (Berkhout et al., 2000; Wei and Liu, 2017). Similar dynamics have since been observed across multiple sectors—including energy, ICT, and mobility—where digitalisation, efficiency gains, and behavioural responses have contributed to increased total resource use (Guzzo et al., 2024; Lange et al., 2021).

From an environmental perspective, REs occur when the benefits of an efficiency improvement are partially or fully offset by increased resource consumption, with a magnitude proportional to the efficiency gain (Zink and Geyer, 2017). However, their implications extend beyond environmental impacts. At the economic level, REs may erode cost savings or stimulate additional production that increases overall market demand, ultimately weakening the intended resource-efficiency gains. From a social perspective, improved affordability or accessibility of products and services can shift consumption patterns in ways that amplify resource use or reinforce unsustainable behaviours. These effects may manifest at multiple levels of analysis—micro (individual products, users, and firms), meso (supply chains and industrial networks), and macro (markets, sectors, and entire economies)—and can influence all three dimensions of sustainability within the triple bottom line (TBL) (Metic and Pigosso, 2022). This multi-level, multi-dimensional nature highlights the systemic relevance of REs and the importance of integrating their assessment into CE and manufacturing decision-making.

Within the CE domain, Zink and Geyer (2017) introduced the concept of the "circular rebound effect", highlighting that rebounds can emerge even when circular strategies are explicitly designed to reduce environmental impacts. They identified two primary mechanisms to explain how REs are triggered within sustainable actions: (i) insufficient substitution, where secondary or recovered products fail to fully replace those made from virgin materials, and (ii) price effects, where cost reductions associated with circular strategies stimulate increased consumption. More recent studies have further expanded these perspectives, revealing that REs can also emerge from sufficiency-oriented (when consumers adopt "doing more with less" practices paradoxically leads to increased use), behavioural (when shifts occur in user habits or consumption patterns after adopting more efficient or circular solutions), and systemic mechanisms (arising from market dynamics, policy interactions, or supply-chain adjustments (Andrew and Pigosso, 2024; Castro et al., 2022; Das et al., 2025; Metic et al., 2024).
Together, these expanded mechanisms illustrate that REs in circular systems extend beyond purely environmental concerns. They reflect complex socio-technical dynamics that influence all dimensions of sustainability, reinforcing the need to understand how efficiency improvements and circular practices may unintentionally trigger rebound pathways across the entire value chain. As a result, REs represent a critical challenge that must be recognised and

proactively addressed to ensure that circular strategies truly deliver their intended environmental, economic, and social benefits.

1.1 Research gaps and objectives

Despite the growing momentum behind the CE, a number of critical knowledge gaps remain, particularly regarding the REs that may arise during CE implementation. REs occur when sustainability-oriented actions trigger systemic responses that offset expected environmental benefits, and recent large-scale analyses reveal their considerable magnitude and variability. Among 530 documented RE instances, the median rebound magnitude is around 47%, meaning that roughly half of the anticipated environmental improvements are typically lost (Andrew and Pigosso, 2024). Estimates range widely, from negative rebounds (enhanced benefits) to extreme backfire effects exceeding 200%, where efficiency improvements actually increase environmental impacts (Andrew and Pigosso, 2024; Guzzo et al., 2025). These findings underscore the urgent need for systematic assessment approaches and harmonised definitions within RE research.

However, REs remain largely overlooked in CE discourse and severely underexplored in manufacturing literature (Madlener and Turner, 2016; Ruzzenenti et al., 2019; Siderius and Poldner, 2021). A central gap lies in the predominantly theoretical nature of existing research, which has produced fragmented conceptualisations and inconsistent terminology but very limited empirical validation (Castro et al., 2022; Makov and Font Vivanco, 2018). Most studies rely on conceptual models, simulations, or hypothetical scenarios, offering limited insights into how REs actually unfold within real manufacturing systems. As a result, there is limited understanding of how CE strategies interact with real manufacturing systems, operational constraints, and organisational behaviours, factors that may trigger complex rebound pathways (Lowe et al., 2024; Metic and Pigosso, 2022). This gap not only restricts empirical knowledge but also contributes to low awareness and weak operational capability among manufacturers, ultimately hindering the practical realisation of CE benefits (Font Vivanco et al., 2022).

Existing RE research is also characterised by a strong focus on consumer behaviour, particularly within product-service systems (PSS), where increased usage frequency or convenience can erode sustainability gains (Chierici and Copani, 2016; Sarancic et al., 2023; Van der Loo and Pigosso, 2024). By contrast, studies addressing REs from the producer or business-to-business (B2B) perspective tend to examine only narrow negative outcomes—such as challenges in adopting new technologies or economic effects of efficiency improvements (Papagiannidis et al., 2023; Skiba et al., 2016), without considering broader systemic or organisational rebound dynamics. Consequently, empirical evidence of RE occurrence in circular manufacturing remains minimal, and the mechanisms through which CE strategies may unintentionally trigger REs in industrial contexts are poorly understood.

Earlier contributions acknowledged the possibility of REs in manufacturing but failed to offer actionable methods to identify or prevent them (Freire-González, 2011; Zink and Geyer, 2017). Although recent work has begun exploring how efficiency improvements in energy- and material-intensive industrial processes may generate REs (Di Domenico et al., 2023), a comprehensive understanding of how and why these effects arise during CE adoption is still lacking. This gap becomes even more critical as companies increasingly implement CE strategies that may interact with complex operational systems, market dynamics, and organisational behaviours—each of which may act as a trigger for rebound pathways.

Importantly, the field still lacks robust, operational tools to detect, assess, and quantify REs in manufacturing. Without accessible methodologies that help explain rebound triggers and raise awareness of potential unintended consequences, companies may unknowingly adopt CE practices that reproduce linear patterns, shift environmental burdens elsewhere in the value chain, or generate additional resource use (Lowe et al., 2024; Madlener and Turner, 2016; Ruzzenenti et al., 2019). The lack of awareness not only limits industrial capability but also restricts the ability of policymakers and researchers to support effective CE transitions.

Taken together, these gaps reveal an urgent need for more empirical research in industrial and B2B settings, more integrated theoretical frameworks that explicitly link CE strategies to specific rebound pathways, approaches that raise awareness of how REs emerge in manufacturing systems; and practical means to support early detection of rebound risks during CE implementation. Without such advancements, CE strategies risk falling short of their intended environmental, economic, and social benefits, ultimately undermining the transition toward more sustainable and resilient industrial systems.

Addressing these gaps is essential for ensuring that CE strategies fulfil their intended environmental, economic, and social benefits rather than inadvertently triggering adverse systemic effects.

To address these gaps, this research aims to develop a tool that supports companies in recognising and detecting the potential REs that may arise during the implementation of circular strategies in the manufacturing industry. By focusing specifically on industrial and B2B contexts—where empirical evidence remains scarce and operational tools are almost entirely absent (Lowe et al., 2024; Van der Loo and Pigosso, 2024) —the study responds to the need for actionable solutions of bridging the persistent divide between conceptual RE theory and its practical application in real manufacturing settings. The tool is conceived not only as a detection instrument but also as a decision-support means driving mechanisms to help firms anticipate, recognise, and interpret rebound pathways before or during CE adoption.

The study has a twofold objective. From a theoretical perspective, it seeks to advance understanding of REs by clarifying where they emerge within manufacturing systems and which mechanisms cause them, and how different CE strategies may interact with organisational, behavioural, and systemic dynamics to trigger rebound pathways. In doing so, the research contributes to consolidating fragmented definitions and strengthening the conceptual connections between CE practices and rebound theory. From an empirical and practical perspective, it aims to raise awareness among practitioners about the unintended consequences that can undermine the environmental benefits of CE initiatives. By offering a structured way to detect REs, the research intends to support more informed and reflexive decision-making during CE adoption, ultimately helping companies detect and prevent counterproductive outcomes and preserve the intended sustainability benefits.

In line with this overarching aim, the following research questions (RQs) guide the study:

RQ1: At which stages of the manufacturing system do REs emerge during the implementation of CE strategies?

RQ2: How are REs triggered during the adoption of CE strategies in the manufacturing industry?

RQ3: How can REs associated with CE strategies be detected in the manufacturing industry?

To address these research questions, the Design Research Methodology (DRM) was adopted (Blessing and Chakrabarti, 2009). DRM provides a structured and rigorous approach for conducting and improving design-oriented research, enabling both theoretical advancement and practical validation, through systematic problem analysis and conceptual development—and practical validation through iterative refinement. Its problem-driven, iterative nature makes it particularly suitable for tackling complex socio-technical challenges such as REs, which require simultaneously understanding causal mechanisms and translating this knowledge into usable tools for industry.

A more detailed description of this methodological approach is presented in the following section.

1.3 Outline of the thesis

This thesis is structured as follows:

- Section 2 presents the research context by outlining the circular strategies currently applied in manufacturing and examining the definitions of REs across different research domains. This section also reviews the main rebound mechanisms discussed in the literature, highlighting how undesired consequences may inadvertently be triggered.
- Section 3 introduces the research methodology. The DRM is adopted and each of its four stages (i.e., Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II) is presented in detail. The section explains the methodological approaches and analytical techniques applied in each stage, including both theoretical methods (such as systematic literature reviews and framework development) and empirical methods (such as expert verification interviews and tool validation activities).
- Section 4 reports the results obtained across all DRM stages. This includes the classification of the rebound mechanisms within manufacturing and the identification of the five CE-RE dimensions, the development of conceptual and reference models, the mapping of circular manufacturing strategies to rebound mechanisms, the creation of the impact model, and the development of the detection-driven tool for REs.
- Section 5 discusses the results, providing an integrated interpretation of the findings in relation to existing literature and industrial practice. The section also outlines the main contributions to both knowledge and practice.
- Section 6 presents the conclusions, summarising the key insights of the thesis, reflecting on its theoretical and practical relevance, and acknowledging the limitations identified throughout the research process.
- Section 7 outlines directions for future research. This includes recommendations for empirical validation of the tool in industrial settings, refinement of sector-specific modules, integration of quantitative indicators, digitalisation of the tool, and the development of actionable mitigation strategies to prevent or reduce potential REs during circular strategy implementation.

2 Research context

This section outlines the contextual foundations of the research. It is organised into two subsections. Subsection 2.1 introduces the CE and its adoption within the manufacturing industry. Subsection 2.2 defines REs in relation to CE, presenting their different types and the underlying mechanisms that explain how REs are triggered.

2.1 Circular economy in manufacturing

CE is commonly defined as a restorative and regenerative paradigm aimed at preserving natural resources, minimising resource inputs, and enhancing the efficiency of industrial systems. CE promotes a shift in the production and consumption pattern from a linear approach, based on a make-use-dispose paradigm, to a circular one, based on a make-reuse-remake-recycle paradigm (Gregson et al., 2015), thereby narrowing, slowing, and closing the materials and energy loops (Bocken et al., 2016; Geissdoerfer et al., 2017). Through the implementation of circular practices, environmental, economic, and social benefits are achievable (Rosa et al., 2019b). In this regard, the reduction in energy and resource consumption, in greenhouse gas emissions, as well as in the utilisation of natural resources and raw materials are among the most beneficial outcomes of CE strategies implementation (Geissdoerfer et al., 2017). The CE principles have been adopted at the micro (by single individuals such as producers and consumers), meso (which includes market network), and macro (such as cities, regions, and nations) levels (Ghisellini et al., 2016). Within the manufacturing sector, CE is increasingly embraced as a means to mitigate environmental burdens and promote sustainable industrial development (Lieder and Rashid, 2016; Garza-Reyes et al., 2019). CE has gained such importance in this sector that scholars now refer to circular manufacturing and related strategies, a field focused on integrating circular strategies into industrial operations (Acerbi and Taisch, 2020).

In circular manufacturing, a wide range of strategies support circularity at different levels of analysis (i.e., micro, meso, and macro levels). At the product level, circular design enables longer product lifetimes through sustainable end-of-life solutions (Albæk et al., 2020; Favi et al., 2019), enhancing repairability, recyclability, modularity, remanufacturability, and adaptability. Disassembly facilitates recovery through subdivision of products into sub-components to facilitate end-of-life processes (Garza-Reyes et al., 2019), while remanufacturing restores used components or products to a like-new state (Sitcharangsie et al., 2019), expanding the 3Rs paradigm into the more comprehensive 9R hierarchy, including rethink, repair, refurbish, remanufacture, repurpose, and recover (Iakovenko et al., 2023).

At the process level, cleaner production (El-Haggar, 2007), lean production (Liang, 2013), and improvements in material and energy efficiency (van Ewijk, 2018) help reduce waste and emissions. Waste management ensures that waste generated is treated responsibly during the process (Rapsikevičienė et al., 2019).

At the business level, the transition toward CE often requires rethinking business models. Circular Business Models emphasise value creation through resource efficiency and how companies manage the circular transition to minimise resource use, preferring servitization (i.e., pay-per-use) (Bocken et al., 2014). often rely on PSS, which shift the focus from selling products to delivering services (Bocken et al., 2014; Tukker, 2004; Blomsma et al., 2018). At this purpose, a PSS is a particular type of business model used to operationalise servitization that combines product and service elements (Tukker, 2004a), addressing consumers' needs while minimising resource use by delivering functionality rather than ownership.

At the supply-chain level, circular manufacturing strategies promote closed-loop systems in which reverse flows return products and materials to manufacturing processes (Lapko et al., 2019; Lieder and Rashid, 2016). These dynamics support industrial symbiosis, where companies exchange energy, materials, and resources to improve collective sustainability performance (Domenech et al., 2019).

The different circular manufacturing strategies were also integrated with methods and decision support tools to generate a framework with the intention of developing a circular manufacturing system (Asif, 2017), which aims to preserve products of high utility and value (Asif et al., 2021). In addition, Acerbi, Sassanelli and Taisch (2022) developed a data model able to map the data and information required to address each of the circular manufacturing strategies. To support manufacturers in their decision-making processes when adopting these strategies, a conceptual data model was developed that identifies the types of data most relevant for enabling circular manufacturing strategies. The circular manufacturing data model integrates and interconnects four key data categories (i.e., product, process, technologies, and management). These categories represent the core domains that manufacturers should monitor during circular manufacturing adoption, providing a structured and comprehensive overview of the information and data needed to effectively operationalize circular strategies.

To ensure a holistic and actionable implementation of circular strategies, circular manufacturing is increasingly framed around four key business processes that structure how circularity is embedded within organisations: business model innovation, production, product design, and procurement (Acerbi and Taisch, 2020; Lieder and Rashid, 2016).

- Business Model Innovation: effective implementation of CE strategies in manufacturing requires rethinking business models, particularly through Circular Business Models that prioritize resource efficiency and effectiveness. In this context, PSS (Blomsma et al., 2018; Kimita et al., 2022; McAloone and Pigosso, 2017; Pigosso and McAloone, 2015) play a key role in decoupling value creation from resource consumption through service-based rather than product-based solutions (Bocken et al., 2014; Tukker, 2004b).
- Production: circular strategies applied in manufacturing processes include cleaner production (El-Haggar, 2007) and lean production, which aims to minimise the impact and eliminate waste across manufacturing processes (Liang, 2013). In addition, material and energy efficiency, targeting reduced consumption (van Ewijk, 2018), and waste management, covering waste treatment and disposal (Rapsikevičienė et al., 2019) are key areas.
- Product design: circular practices are integrated at the beginning of a product's life to extend the lifespan of products, components, and materials (Pigosso et al., 2017). To preserve their value, products are

designed for repairability, recyclability, remanufacturability, modularity, robustness, and adaptability, enabling multiple lifecycles and reducing dependency on raw resources (Albæk et al., 2020; Pieroni et al., 2018).

- Procurement: CE strategies in manufacturing extend to the entire supply chain, enabling closed-loop systems where reverse flows return products to the manufacturing process. This facilitates industrial symbiosis, wherein different industries exchange resources, such as energy, water, and materials, enhancing environmental and economic performance (Domenech et al., 2019).

2.2 Rebound effects in circular economy

REs arise when actions intended to improve sustainability inadvertently stimulate behavioural or systemic responses that offset the expected environmental benefits. Originating in energy economics, RE was defined as an improvement in energy efficiency that leads to a reduction in the price of products or services and an unexpected increase in consumer demand (Berkhout et al., 2000). These unintended and unavoidable increases in demand reduce the predicted environmental benefits as a negative consequence of enhanced efficiency (Zink and Geyer, 2017). Within CE, REs manifest when circular strategies—such as reuse, remanufacturing, or resource efficiency—generate higher levels of consumption or production, thereby diminishing the net sustainability benefits (Castro et al., 2022).

Within the concept of the "circular rebound effect", two main mechanisms were introduced, which represent the underlying causal explanations through which REs arise: insufficient substitution, when secondary goods fail to fully replace those made from virgin materials, and price effects, where lower costs of circular products induce additional consumption (Zink and Geyer, 2017). More recent studies have further expanded these perspectives, revealing that REs can also emerge from sufficiency-oriented (when consumers adopt doing more with less practices), behavioural (when shifts occur in user habits or consumption patterns after adopting more efficient or circular solutions), and systemic mechanisms (arising from market dynamics, policy interactions, or supply-chain adjustments) (Andrew and Pigosso, 2024; Castro et al., 2022; Das et al., 2025; Metic et al., 2024) (Table 1).

Table 1. Summary of the main rebound mechanisms

Mechanism	Description	Causal driver	Reference
Insufficient Substitution	Secondary (recycled/refurbished) goods fail to fully replace virgin goods.	Circular products used as add-ons rather than replacements.	Zink and Geyer (2017)
Price Effects	Lower costs of circular or used products increase purchasing power.	Savings are re-spent on more of the same or different goods.	Zink and Geyer (2017)
Sufficiency-oriented	"Doing more with less" leads paradoxically to increased consumption.	Sufficiency behaviours generating higher activity levels.	Andrew and Pigosso (2024)
Behavioural	User habits shift after adopting efficient or circular solutions.	Increased product or service usage.	Castro et al. (2022), Metic et al. (2024)
Systemic	Large-scale effects arising from market, supply-chain, or policy shifts..	Market interactions, policy shifts, or macroeconomic adjustments.	Das et al. (2025)

In the literature, different types of RE were detected with reference to the overall demand for products or services. According to Greening, Greene and Difiglio, (2000) four different types of RE were considered in the context of the present research: direct, indirect, economy-wide, and transformational, each linked to demand responses at different levels of the system and associated with specific triggering mechanisms.

Direct REs refer to an increase in demand and consumption of the same product due to an efficiency improvement leading to a related enhancement in price, production, or perception, involving at the micro level the producer and consumer (Otto et al., 2014). One example is the electric car. In fact, greater efficiency in the use of an alternative fuel leads to more driving (Walnum et al., 2014). In fact, improved production leads to a reduction in the cost of production or acquisition, which increases the demand for production (price mechanism) (Greening et al., 2000; Sorrell, 2007). The time mechanism means that efficient use or production leads to increased consumption or production, respectively (Sorrell and Dimitropoulos, 2008). The income mechanism is generated by a lower purchase price that increases demand, while the output mechanism is caused by an increase in supply that reduces production costs and consequently increases production (Greening et al., 2000; Sorrell, 2007). Consumer perceptions also increase demand (motivational mechanism) (Figge et al., 2014). The symbiotic mechanism refers to the opportunity cost that produces a higher-than-expected use of resources (Figge and Thorpe, 2019).

Indirect REs occur when an improvement in production in one product generates an increase in demand or supply of other products at meso level, involving consumer and producer within the market of interest (Sorrell, 2007). For instance, the electric scooter can substitute walking, cycling, or public transportation, even for short routes. The mechanisms of indirect effects involve an improvement in the efficiency of one product leading to an increase in demand or supply of other products, as a negative effect. The re-spending mechanism means that, due to savings in the purchase of one product, the consumer increases demand for other products (Sorrell, 2007). In the re-investing mechanism, the producer reduces production costs in one chain and uses them in other product chains (Borenstein, 2015; Santarius, 2012). The substitution mechanism refers to switching to a more resource-intensive product or service despite cost reductions or improvements in the resource use of another product (Sorrell and Dimitropoulos, 2008; Turner and Hanley, 2011). Consumption accumulation means that the efficiency of a product or service doesn’t replace traditional ones but complements them (Santarius, 2012). Imperfect substitution occurs when secondary goods are insufficient to replace primary goods and become less desirable (Warmington-Lundström and Laurenti, 2020; Zink and Geyer, 2017). The motivational mechanism is generated by consumer preferences that lead to the consumption of other products (Santarius and Soland, 2018).

Economy-wide REs occur at the macro level, where interactions among market actors (i.e., across cities, regions, or nations) amplify the combined effects of direct and indirect rebounds. In this broader context, efficiency improvements influence supply and demand across entire markets, leading to increased production, consumption, and resource use (Sorrell and Dimitropoulos, 2008). As proof, photovoltaic panels produce energy efficiently while increasing energy demand and use. Indeed, consumption efficiency, as a mechanism, leads to greater demand for resources (Santarius, 2012). The resource market mechanism is caused by a lower resource price, leading to higher utilisation (Walnum et al., 2014). In the composition mechanism, improved production leads to lower prices and a consequent increase in demand (Turner, 2013; van den Bergh, 2011). The mechanism of structural change involves improved production, leading to increased resource consumption (Jaccard and Bataille, 2000). In the new market mechanism, the improvement of the economy as a whole converts existing production by adding and developing new large-scale markets. Market price mechanisms increase profits and revenues and lead to re-spending and re-investing effects (Santarius, 2012). The cross-factor mechanism refers to the improvement of production factors that increase demand and trigger economic growth (Santarius, 2012; Walnum et al., 2014). The frontier mechanism means that new products and industries produce an effect on production that has an impact on the demand for resources. In the international mechanism, resource use increases when the international transfer of efficient technologies does not impact resource production (Freeman, 2018).

Transformational REs refer to wide-scale changes in the economy and society due to efficiency improvements involving consumers' preferences, institutions, production organisations, and technological progress (Greening et al., 2000; Polimeni et al., 2012), so as to affect a global level. An example could be second-hand clothes that offer an additional alternative to new clothes, increasing production and demand even more (Table 2).

Table 2. Summary of the four types of REs

Type of RE	Definition	Example
Direct effect	refers to a demand increase of the same product due to an efficiency in price, production, or perception (Otto et al., 2014).	A consumer buys a highly fuel-efficient hybrid car but ends up driving more kilometres than before because the cost per mile has dropped (Walnum et al., 2014).
Economy-wide effect	involves direct and indirect effects leading to changes in demand and supply at the market level (Santarius, 2012).	The widespread adoption of electric scooters shifts urban transport dynamics so much that people stop walking or using buses.
Indirect effect	is an improvement in production of one product that causes an increase in demand or supply of other products (Sorrell, 2007).	A household saves money on their monthly bill by installing photovoltaic panels, then uses those savings to other activities.
Transformational effect	refers to wide-scale changes in the economy and society caused by an improvement in efficiency (Greening et al., 2000).	The rise of second-hand clothing changes the "throwaway" culture; instead of buying less, consumers buy more items overall.

Across these types, REs can manifest at micro, meso, and macro levels and may affect all three dimensions of sustainability within the TBL (i.e., environmental, economic, and social) (Metic and Pigosso, 2022). Their magnitude is highly variable, reinforcing the need to understand how rebound mechanisms and types interact, especially in CE and manufacturing contexts, where efficiency improvements and circular strategies can unintentionally trigger REs at multiple stages of the value chain, ultimately undermining not only environmental gains but also economic and social sustainability outcomes.

Understanding how different types of REs emerge requires examining the rebound mechanisms that are considered as an external input, since they represent the qualitative causal connections between interdependent elements that lead to specific effects (Lange et al., 2021). Rebound mechanisms represent the interdependent conditions, responses, and feedback loops that translate an efficiency improvement or a circular strategy into an unintended increase in consumption. To capture the full range of possible rebound pathways, in the literature, three recent studies have classified and categorized the different rebound mechanisms, including those identified by Guzzo et al. (2024), Metic and Pigosso (2022), and Van der Loo and Pigosso (2024). These studies provide comprehensive literature reviews of rebound mechanisms identified across various domains, with demonstrated applicability to the CE context. Guzzo et al. (2024) and Metic and Pigosso (2022) focused specifically on the producer perspective, making them particularly relevant to this study's interest in identifying potential REs within the manufacturing sector. In contrast, Van der Loo and Pigosso (2024) examined the behavioural aspects that lead to a RE from the consumer side, offering insights into consumer behavioural actions, some of which may also be relevant to producers, particularly where producer decisions may be influenced by similar behavioural drivers.

The producer-oriented mechanisms (Table 3) included those describing efficiency improvements in one of the business processes. These improvements could result in increased output and, consequently, greater overall resource consumption. Symbiotic effects, which refer to higher-than-expected resource use, were also included. Additionally, mechanisms related to labour income with limited labour supply were considered. These describe macroeconomic scenarios where efficiency gains lead to higher wages, greater disposable income, or reduced working hours. They are included even if they are considered outside the scope of operational and strategic decision-making at the firm level.

Table 3. Rebound mechanisms from producer perspective

Rebound mechanisms	Definition	Adapted from
Price	Lower production costs, resulting in higher resource demand for production	(Metic and Pigosso, 2022)
Output	Lower production cost leads to enhanced supply of the same products	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Time	Efficient manufacturing enables higher levels of production	(Metic and Pigosso, 2022)
Sufficiency/Demand adjustment initiated by sufficiency/Supply adjustment	Sufficiency strategies by one producer can be offset by an increase in supply from another producer	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Symbiotic	The value created a higher-than-expected use of the same resources	(Metic and Pigosso, 2022)
Re-investing	Lower production cost leads to enhanced supply of other products	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Substitution/Factor substitution	Lower production costs enable the demand for other more resource intensive products	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Imperfect substitution	The use of secondary resources leads to higher primary production due to lower quality	(Metic and Pigosso, 2022)
Consumption efficiency	More efficient consumption increases the demand for resources	(Metic and Pigosso, 2022)
Resource market/Demand adjustment initiated by sufficiency	Efficiency improvement reduces resource use at the market level, but lower price increases resource use	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Composition	Efficiency improvements in production lead to price reduction, stimulating higher demand	(Metic and Pigosso, 2022)
Structural change	Efficiency improvement shifts production patterns, increasing resource consumption	(Metic and Pigosso, 2022)
New market	Efficiency drives changes in the structure of the economy, converting existing production and creating new markets	(Metic and Pigosso, 2022)
Market price	Efficiency increases consumer re-spending and re-investment, leading to higher consumption.	(Guzzo et al., 2024; Metic and Pigosso, 2022)

Cross-factor/ Cost-dependent output	Efficiency improvements in one factor enhance other production factors, increasing output and resource use.	(Guzzo et al., 2024; Metic and Pigosso, 2022)
Frontier	Efficiency improvement enables the creation of entirely new products, increasing the impact on resource demand	(Metic and Pigosso, 2022)
International	Efficiency improvements transferred internationally without adequate incentives can raise global resource use.	(Metic and Pigosso, 2022)
Demand adjustment with investment adjustment	Lower demand reduces prices, which later boosts consumption, increasing resource use.	(Guzzo and Pigosso, 2024)
Re-design	Efficiency leads to feature expansion in products, reducing overall efficiency.	(Guzzo and Pigosso, 2024)
Producer-induced demand adjustment	An efficiency action reduces demand for a process, leading to a low excess of supply or demand. This results in a price decrease for the process, which stimulates additional demand from other companies, ultimately increasing overall demand for the process and general resource consumption	(Guzzo and Pigosso, 2024)
Economies of scale	Efficiency reduces costs, increasing demand and resource consumption.	(Guzzo and Pigosso, 2024)
Labour income	Lower costs raise wages, increasing disposable income and consumption.	(Guzzo and Pigosso, 2024)
Labour income with limited labour supply	Reduced work hours and higher wages boost demand and resource use.	(Guzzo and Pigosso, 2024)

The consumer motivational mechanisms (Table 4) included those that could reasonably be mapped onto producer behaviour were included. Some mechanisms are more related to consumer behaviour. These include, for example, need satisfaction, negative stereotypes, diffusion of responsibility, and mental accounting, which, while relevant to consumer decision-making, lack a clear pathway to integration into business-level operations in manufacturing firms. Others, such as information overload, perceived behavioural control, and social practice theory, were not included in this study due to their strong focus on individual or social psychological dynamics, which are less transferable to organizational contexts.

The extension of consumer-oriented motivational mechanisms to producers is grounded in the recognition that organizational choices ultimately reflect human perceptions, motivations, and cognitive biases, which can act as potential drivers of REs (Fleck-Baustian et al., 2025). Moreover, as several studies in organizational and managerial behaviour have shown, decision-makers within firms often display psychological patterns similar to those of consumers (Hristov et al., 2022), which may foster the adoption of CE practices but also increase the likelihood of REs. In sustainability management, this dynamic is evident when managers perceive the implementation of a single circular initiative as sufficient proof of environmental responsibility, thereby legitimising other resource-intensive practices, an organizational analogue of consumer moral licensing (Mazar and Zhong, 2010). These behavioural dynamics illustrate that, even in B2B and manufacturing contexts, REs can emerge from the cognitive and motivational mechanisms (Table 4) of individual actors within organizations who make or influence production and investment decisions.

Table 4. Rebound mechanisms from consumer perspective applied to producer

Rebound mechanisms	Definition	Adapted from

Moral licensing	Producers may feel justified in increasing emissions when they create circular products, perceiving their sustainable solutions as permission for environmentally harmful behaviour	(Van der Loo and Pigosso, 2024)
Contribution ethics	Sustainable behaviour may reduce motivation for further pro-environmental actions.	(Van der Loo and Pigosso, 2024)
Single-action bias	One sustainable act is seen as sufficient, reducing further action.	(Van der Loo and Pigosso, 2024)
Need satisfaction	Unsatisfied needs from sustainable solutions may increase consumption.	(Van der Loo and Pigosso, 2024)
Response efficacy	Sustainable design may mislead awareness of effective environmental actions	(Van der Loo and Pigosso, 2024)
Negative associations	Perceived low quality or high cost in sustainable products reduces engagement.	(Van der Loo and Pigosso, 2024)
Negative stereotypes	Stereotypes linked to sustainable solutions reduce the adoption of sustainable behaviour.	(Van der Loo and Pigosso, 2024)
Perceived behavioural control	Sustainable design can make people feel less able to act pro-environmentally.	(Van der Loo and Pigosso, 2024)
Diffusion of responsibility	Responsibility is shifted to others, reducing personal environmental action, and leading to a decline in pro-environmental behaviours.	(Van der Loo and Pigosso, 2024)
Motivational crowding	Institutional rewarding may reduce intrinsic motivation to act sustainably.	(Van der Loo and Pigosso, 2024)
Information overload	Misunderstanding of the sustainable solution can lead to confusion or inaction.	(Van der Loo and Pigosso, 2024)
Time discounting	Immediate benefits outweigh perceived future gains from sustainable actions.	(Van der Loo and Pigosso, 2024)
Mental accounting	Cost savings from sustainability may be re-spent in unsustainable ways.	(Van der Loo and Pigosso, 2024)
Cognitive dissonance	Sustainable solutions may be used to justify continued harmful behaviours.	(Van der Loo and Pigosso, 2024)
Social practice theory	Sustainable solutions can influence broader society, leading to unsustainable outcomes despite sustainable intentions.	(Van der Loo and Pigosso, 2024)
Social acceleration	Cultural pressures to produce more undermine sustainability gains.	(Van der Loo and Pigosso, 2024)
Behavioural income effect	Savings from pro-environmental shifts are re-spent, increasing resource use.	(Van der Loo and Pigosso, 2024)

Taken together, these perspectives highlight that REs are multifaceted phenomena arising from intermixed structural, economic, and behavioural mechanisms, underscoring the importance of systematically identifying rebound risks when designing and implementing circular strategies in manufacturing systems.

3. Research methodology

To investigate how REs emerge within circular manufacturing and how they can be systematically detected, this study applies a structured research methodology grounded in the DRM (Blessing and Chakrabarti, 2009) framework. The following section describes the methodological approach, outlining the phases and analytical steps undertaken.

The DRM framework was selected because it enables a rigorous, systematic, and iterative process for conducting and improving design-oriented research. It supports both the development of theoretical foundations and their translation into practical solutions. In particular, this methodology provides a clear structure for analysing the existing situation, defining the desired situation, and developing support tools that bridge the gap between the two. Compared with alternative research approaches, such as case study research, action research, or broader Design Science Research (Peffers et al., 2012) frameworks, DRM offers a more fine-grained, phase-based structure that is especially suited for investigating complex socio-technical phenomena like REs in circular manufacturing. While design science research also targets the creation and evaluation of artefacts, its process models are typically more general. DRM, by contrast, provides clearer guidance on tracing how empirical insights inform the formulation of requirements, the development of support tools, and their subsequent evaluation. This explicit emphasis on iterating between understanding and improving the existing situation makes DRM particularly appropriate for studies aiming to develop methodological tools grounded in both theory and industrial practice.

The DRM framework consists of four iterative stages:

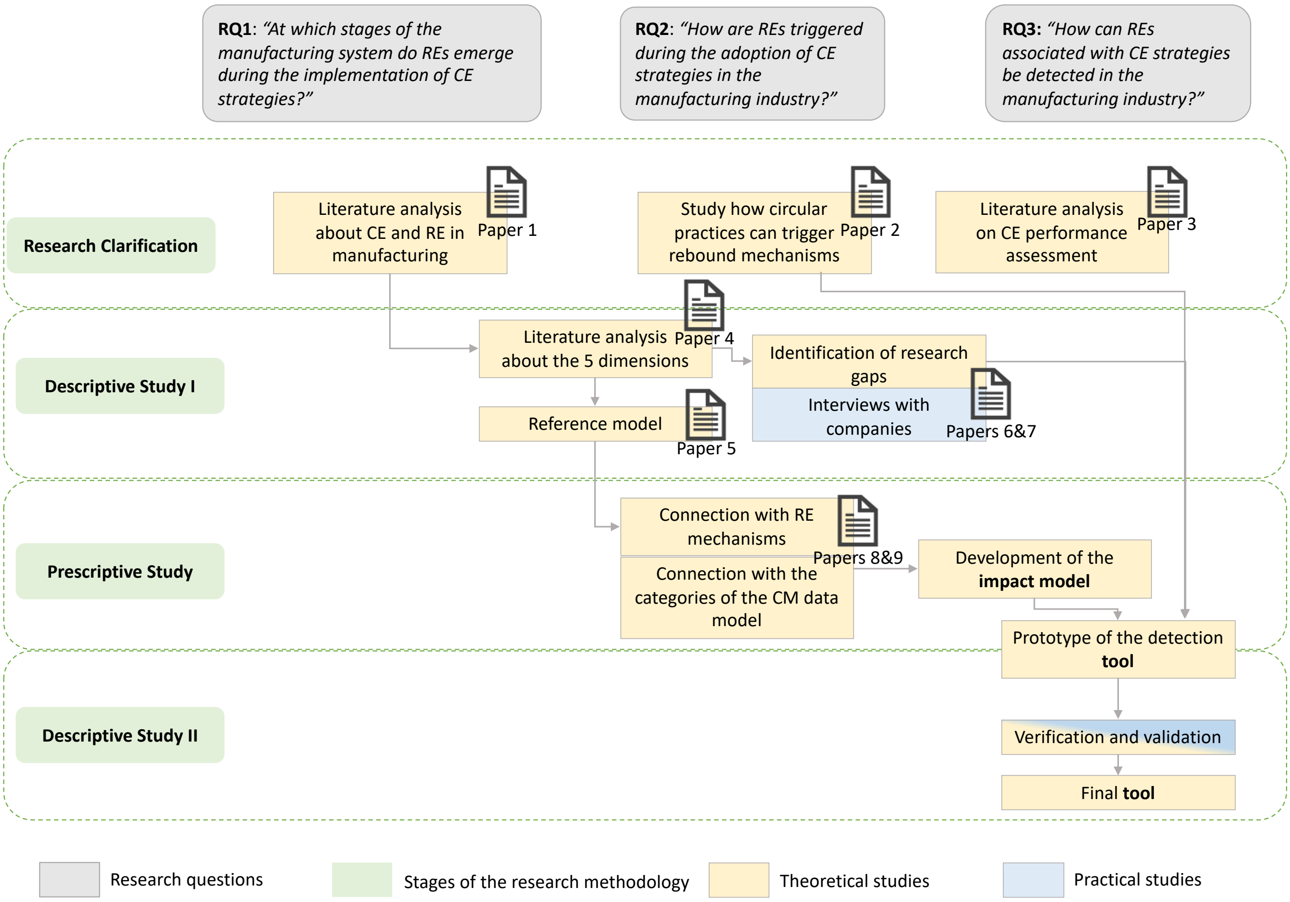
- Research Clarification, which defines the main focus and objectives of the study based on a preliminary literature review;
- Descriptive Study I, which provides a comprehensive analysis of the current situation to deepen understanding of the research problem;
- Prescriptive Study, which outlines a design support based on the synthesis of insights gathered in the previous stages;
- Descriptive Study II, which evaluates and validates the proposed support.

The three research questions identified in the previous section were addressed across the DRM stages using different methodologies (Figure 1).

The first research question, RQ1: *Where can REs occur during the implementation of CE strategies in the manufacturing industry?,* was addressed during the Research Clarification stage.

The second research question, RQ2*: How are REs triggered during the adoption of CE strategies in the manufacturing industry?*, was addressed across the first three stages of the DRM. These stages focused on analysing the current situation, identifying the underlying mechanisms that give rise to REs, and defining the elements required to shape the desired situation, thereby laying the foundation for the development of a support tool.

The third research question, RQ3: *How can REs associated with CE strategies be detected in the manufacturing industry?,* was explored in the final two stages, which concentrate on developing the desired situation and introducing the support intended to fulfil the main objective of this research.



Paper 1 Investigating the circular economy's rebound effect in manufacturing: a systematic literature review

Paper 2 Rebound Effects in Circular Manufacturing: overview of potential rebound mechanisms activated by circular strategies across key business processes

Paper 3 Mapping the relations between the circular economy rebound effects dimensions: A systematic literature review

Paper 4 The Evolution of Circular Economy Performance Assessment: A Systematic Literature Review

Paper 5 Developing the reference model to decode the occurrence of Rebound Effect of Circular Economy

Paper 6 Circular Economy Rebound Effect: Theoretical Implications and a Research Agenda

Paper 7 Assessing rebound effects in circular economy: insights from the automotive industry

Paper 8 Detailing the Circular Economy Rebound Effect reference model through Rebound Effect mechanisms

Paper 9 Exploring the Pairing of Circular Manufacturing Data Categories and Rebound Effect Factors

Figure 1. Overview of the adopted Design Research Methodology.

In the following paragraph, the different DRM stages and the methodologies applied within each of them are presented in detail.

3.1 Stage 1: Research Clarification

The first DRM stage, *Research Clarification*, focused on examining the existing situation to identify where REs may arise during the implementation of CE strategies in the manufacturing industry and to understand the rebound mechanisms through which they are triggered.

The design process adopted in this first stage is illustrated in Figure 2.

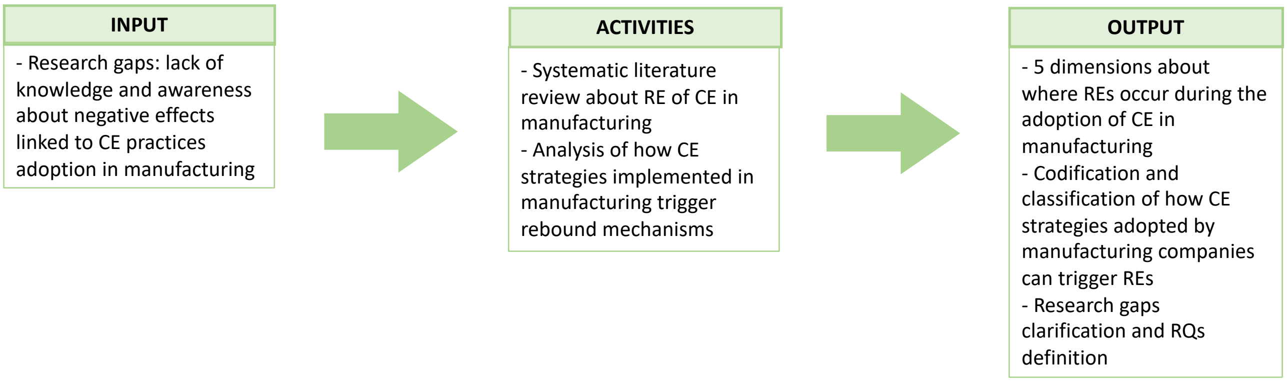


Figure 2. Stage 1: Inputs, Activities, Outputs.

To determine the contexts in which REs can emerge, an initial systematic literature review was conducted following the five-step approach proposed by Biolchini et al. (2005) (Figure 3).

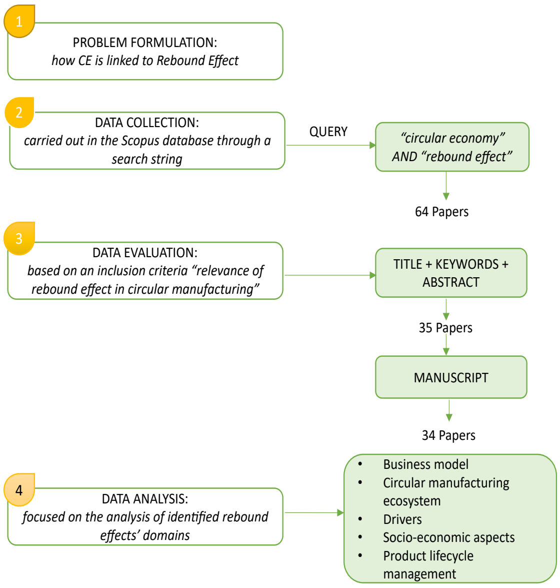


Figure 3. Research methodology approach

The first step involved defining the central issue of the review, namely the relationship between CE and RE within manufacturing. In the second step, data collection was carried out using a specific search string in the Scopus database: *"CIRCULAR ECONOMY" AND "REBOUND EFFECT"*. The query was applied to all document types, without time restrictions, up to May 2023, and filtered for English-language publications, resulting in 64 documents.

In the data evaluation phase, documents were screened according to a single inclusion criterion: the relevance of RE within circular manufacturing. This screening reduced the sample to 34 documents. Subsequently, in the data analysis step, these papers were examined and classified into five dimensions (i.e., Business model, Drivers, Product lifecycle management (PLM), Circular manufacturing ecosystem, and Socio-economic aspects) each capturing different aspects linking CE and RE.

These five dimensions formed an initial reference model, representing the current state derived from the literature and serving as a baseline for subsequent refinement and development.

To examine how CE strategies implemented in manufacturing trigger rebound mechanisms, a two-step methodology was applied.

The first step mapped CE strategies across four key business processes—business model, production, product design, and procurement (Porter, 1985). Strategies relevant to circular manufacturing were identified using Acerbi and Taisch (2020), whose work offers an empirically grounded overview of practices already adopted in manufacturing industry. To organise these strategies systematically, the Circular Strategies Scanner (Blomsma et al., 2019) was used. This framework was selected because it was developed specifically for manufacturing, and aligns closely with the strategies outlined by Acerbi and Taisch (2020). This alignment ensures that the selected strategies are both theoretically robust and practically relevant, allowing for a clear and operationalizable mapping of circular manufacturing practices.

The Circular Strategies Scanner categorized strategies according to their contribution to value retention across the product lifecycle, identifying four main areas of intervention, 1) rethink and reconfigure, 2) restore, reduce and avoid, 3) recirculate parts and products, and 4) recirculate materials, each linked to strategies aimed at narrowing, slowing, and closing resource loops. Its structure facilitates a clear mapping of circular strategies—such as servitization, remanufacturing, lean production, and industrial symbiosis—across business processes. The outcome of this step resulted in a table that presents business processes in rows and the categories of the Circular Strategies Scanner in columns. In the intersection between columns and rows, the corresponding circular manufacturing strategies were inserted (i.e., those linked to the Circular Strategy Scanner's categories and applicable to the specific business process). This structure enables a systematic and comprehensive mapping of CE practices in manufacturing across key business processes.

The second step identified the rebound mechanisms that may be triggered by these strategies. Rebound mechanisms were considered external inputs describing the qualitative causal connections between interdependent elements through which REs occur (Lange et al., 2021). To capture both producer and consumer dynamics, mechanisms were selected from three recent studies: Guzzo et al. (2024), Metic and Pigosso (2022), and Van der Loo and Pigosso (2024). These studies were chosen because they provide comprehensive literature reviews of rebound mechanisms identified across various domains, with demonstrated applicability to the CE context. Guzzo et al. (2024) and Metic and Pigosso (2022) focused specifically on the producer perspective, making them particularly relevant to this study's interest in identifying potential REs within the manufacturing sector. In contrast, Van der Loo and Pigosso (2024) examined the behavioural aspects that lead to a RE from the consumer side, offering insights into consumer behavioural actions, some of which may also be relevant to producers, particularly where producer decisions may be influenced by similar behavioural drivers.

From the 40 mechanisms identified in the three reference studies, a screening process based on conceptual alignment with circular manufacturing and applicability to business processes resulted in a final selection of 30 mechanisms—23 producer-oriented and 17 originally consumer-oriented motivational mechanisms considered transferable to producer behaviour. Each mechanism was assessed using two criteria: (1) coherence between the mechanism's definition and the underlying logic of circular strategies in manufacturing, and (2) applicability to actions typically carried out within manufacturing business processes, namely business model, production, product design, and procurement. Only mechanisms satisfying at least one of these conditions were retained.

Producer mechanisms that fell outside the scope of firm-level operational or strategic decision-making—such as symbiotic effects or mechanisms based on labour income dynamics—were excluded. Likewise, several consumer motivational mechanisms were removed due to their limited relevance to organisational contexts. These included mechanisms such as need satisfaction, negative stereotypes, diffusion of responsibility, and mental accounting, which are strongly linked to individual consumer behaviour and lack a clear pathway to business-level decision-making. Additional mechanisms—such as information overload, perceived behavioural control, and social practice theory—were also excluded because they rely on individual or social psychological dynamics that cannot be readily transferred to organisational settings.

The inclusion of the remaining consumer-derived mechanisms is supported by the growing recognition that organisational choices are shaped by human perceptions, motivations, and cognitive biases (Fleck-Baustian et al., 2025). Research in organisational and managerial behaviour shows that decision-makers within firms often follow psychological patterns similar to those of consumers (Hristov et al., 2022), which can both facilitate CE adoption and increase the risk of REs. This is evident in sustainability practices, where managers may treat the implementation of a single circular initiative as sufficient proof of environmental responsibility, thereby legitimising more resource-intensive activities—an organisational analogue of moral licensing (Mazar and Zhong, 2010).

These dynamics illustrate that, even in B2B and manufacturing contexts, REs may arise from the cognitive and motivational mechanisms enacted by individuals and groups within firms who influence production and investment decisions. For this reason, the present research conceptualises producer behaviour as the collective outcome of decision-making processes shaped by these mechanisms.

In parallel with the identification of CE strategies and related rebound mechanisms, a third inquiry was conducted to examine how CE performance has been assessed in recent years and to identify which methods may support the evaluation of potential REs. This review was necessary because assessing REs requires performance measurement approaches capable of capturing CE outcomes across lifecycle stages. For this reason, the study analysed the evolution of CE performance assessment methods from the third quarter of 2018 to the second quarter of 2024. A systematic literature review was conducted following the steps proposed by Denyer and Tranfield (2009) (Figure 4).

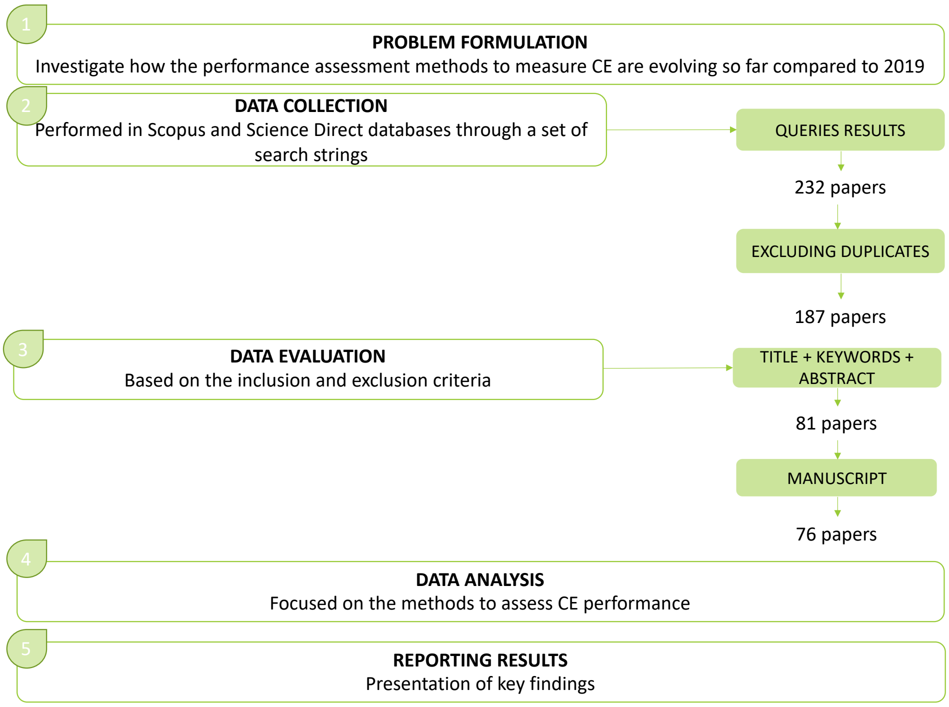


Figure 4. Systematic literature review research process

Following Denyer and Tranfield (2009), the review consisted of five main phases. The first phase was to formulate the problem underlying the review. This dealt with the need to examine the evolution of the CE performance assessment methods proposed so far with respect to 2019, due to the presence of another literature review that identified the most effective methods for assessing CE performance and how they could be integrated for comprehensive evaluation (Sassanelli et al., 2019a).

The second step concerned the data collection, which was performed in Science Direct and Scopus databases from the third quarter of 2018 up to the second quarter of 2024. The search was conducted using the same queries from Sassanelli et al. (2019a), which were a combination of different keywords as shown in Table 5, all of which included "circular economy" or a synonym (i.e., "end of life") combined with "performance", "assessment", and "methodology". The numbers in parentheses indicate, for each query, the numbers of articles selected that made up the final sample for analysis without duplicates and according to the inclusion and exclusion criteria. A total of 187 documents were found in the two academic search engines without redundancies (n=45).

The third step referred to the selection of the collected data. Articles from international journals and conferences were included, while grey literature and non-English language publications were excluded. One of the main inclusion criteria was to consider articles that proposed methodologies for measuring CE performance with an assessment of the strength of the evidence. According to these criteria, a total of 76 articles were selected to constitute the final sample used for conducting the analysis.

Then, the final sample of papers was analysed from a bibliometric perspective to outline the key quantitative characteristics of the considered research domain. For each article, the following aspects were considered: (i) the year of publication; (ii) the document type (i.e. conference paper, journal paper, or book chapter); (iii) the research type (i.e., theoretical assessment, analytical assessment, action research, and application case); (iv) the journal in which the paper was published; (v) the Country of affiliation of the first author; (vi) the Industry considered.

A content analysis was then conducted to identify the most recurring themes in the analysed domain and, in line with the study's objective, to trace the evolution of CE performance assessment. In this process, the following aspects were considered for each work: (i) the methodology used to assess CE performance; (ii) the TBL dimension considered in the evaluation (environmental, economic, social); (iii) the type of variables used in any indicators or metrics employed (energy, material, pollution); (iv) lifecycle stages considered to assess CE performance (beginning of life (BoL) with design and production, middle of life (MoL) with use and maintenance, end of life (EoL) with disposal, recycling, or repurposing). Moreover, each paper was categorised according to its nature, i.e. theoretical or empirical. Notably, the same dimensions of analysis as in the previous work (Sassanelli et al., 2019a) were used to ensure comparability of the results and to clearly highlight the evolution of research in this field.

The final step consisted in presenting the key findings identified during the analysis, grouping selected papers by type of performance assessment method proposed for measuring CE.

Table 5. Search strings

N.	Search	Science Direct	Scopus
1	"circular economy" AND "performance assessment" AND "methodology"	6 (2)	28 (14)
2	"circular economy assessment"	4 (3)	44 (22)
3	"circular economy performance"	1 (0)	73 (27)
4	"end of life" AND "performance assessment" AND "methodology"	0 (0)	13 (1)
5	"end of life assessment"	2 (2)	15 (2)
6	"end of life performance"	2 (1)	15 (2)
TOTAL third quarter 2018- second quarter 2024 after duplication removal		**10**	**177**
TOTAL third quarter 2018- second quarter 2024 after not consistent types of documents (conference proceedings review discarded)		**10**	**173**
TOTAL (total after selection based on the three criteria)		**44 (8)**	**188 (68)**

The outcomes of this review provide insight into which CE performance assessment approaches may be suitable for evaluating potential REs and thus support the refinement necessary to develop the final output.

3.2 Stage 2: Descriptive Study I

The second DRM stage, *Descriptive Study I*, focused on conceptualising the study and interpreting the research objectives to define the current situation. This stage combined theoretical and empirical work, as illustrated in the design process (Figure 5).

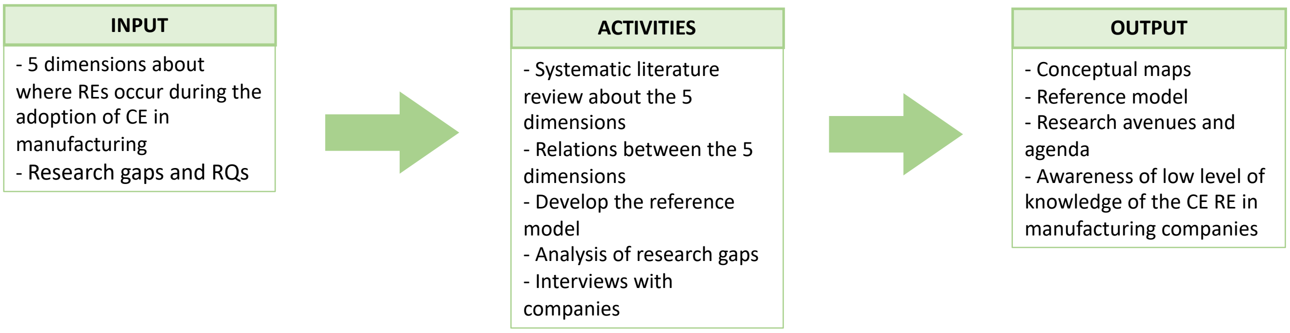


Figure 5. Stage 2: Inputs, Activities, Outputs.

3.2.1 Systematic literature review on the five dimensions of CE and RE

The first activity deepened the investigation of the five CE-RE dimensions previously identified, with the aim of mapping their interconnections and developing a reference model representing the current state. In parallel, the research domain was further examined by identifying key research gaps and assessing industry awareness regarding potential REs emerging from CE implementation.

To explore the five dimensions, a systematic literature review was conducted following the five-step method proposed by Biolchini et al. (2005) (Figure 6). The central objective of the review was to understand the characteristics and interrelations among the CE-RE dimensions and to support the development of a conceptual map capturing these relations.

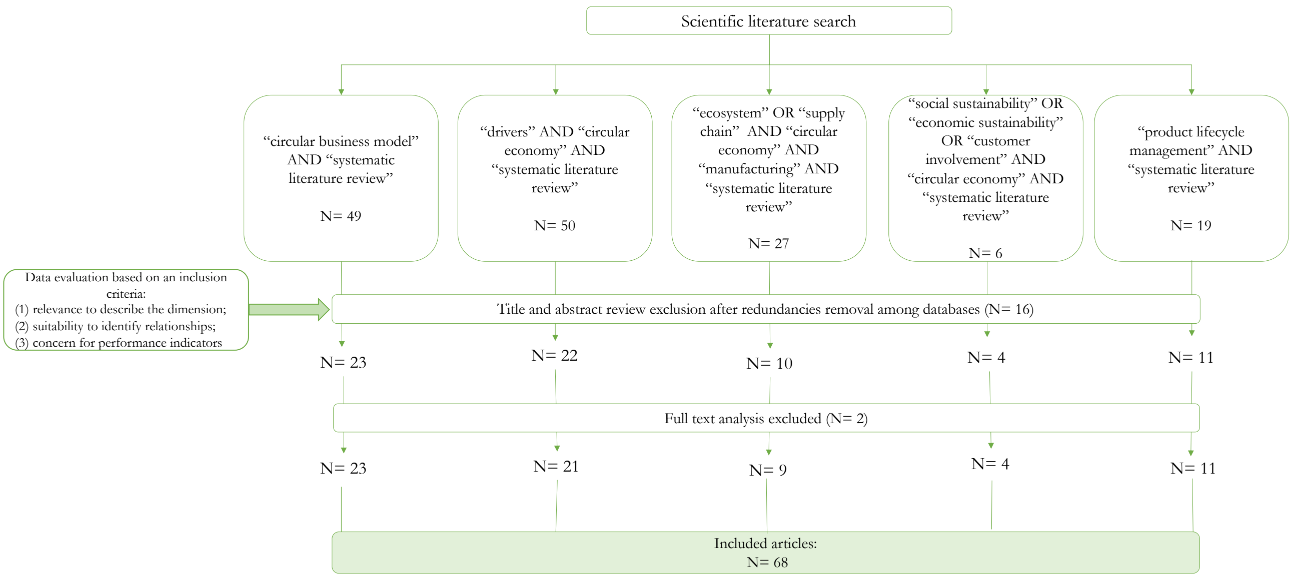


Figure 6. Systematic literature approach adopted

Data collection was carried out in July 2023 using five search strings in the Scopus database (*"circular business model" AND "systematic literature review"*; *"drivers" AND "circular economy" AND "systematic literature review"*; *"ecosystem" OR "supply chain" AND "circular economy" AND "manufacturing" AND "systematic literature review"*;

"social sustainability" OR "economic sustainability" OR "customer involvement" AND "circular economy" AND "systematic literature review"; "product lifecycle management" AND "systematic literature review") each combining *"systematic literature review"* with one CE-RE dimension (*"circular business model", "drivers", "circular manufacturing ecosystem", "social and economic sustainability",* and *"product lifecycle management").* When these terms did not inherently include circular economy aspects, the keyword *"circular economy"* was added.

The queries were performed across all types of scientific papers published up to July 2023, with a filter on the English language, leading to a set of 135 documents, excluding duplicates (n= 16).

Documents were screened according to three inclusion criteria aligned with the review scope: exploring the characteristics of at least one CE-RE dimension, identifying relations between dimensions, and contributing to performance indicators for circularity assessment. After title–abstract–keyword and full-text screening, 68 papers were selected.

The analysis involved both descriptive and thematic components. Descriptive analysis examined publication trends, authorship, and document types. Thematic analysis organised papers by content, objectives, and outputs, enabling the identification of factors within each dimension and the relations among them.

Finally, the thematic analysis was conducted, and relations between dimensions were detected in the selected papers. These relations were first analysed individually and then arranged together visually in a conceptual map, following the DRM (Blessing and Chakrabarti, 2009). A set of conceptual maps is made up of factors and arrows. Two factors were assigned to each selected paper, formed by elements belonging to two different dimensions and linked to each other by a cause-and-effect relation, where the cause represents the origin of the arrow and the effect is the destination. The reference paper was shown on the arrow along with an identifying number, while at the arrowhead, a positive or negative sign was placed. The sign denotes the type of contribution that a specific factor provides to the other to which it is related, evaluating if the impact produced is good for achieving sustainability or not. The relations were grouped into macro-clusters by affinity and similarity. The widest ones were isolated based on their unveiled multiple relations, while those characterized only by single relations were gathered based on common dimensions. Finally, for each relation between factors in the conceptual maps, the possible type of RE (i.e., direct, indirect, economy-wide, and transformational) which each of these relations could generate was unveiled.

3.2.2 Developing the reference model

The conceptual maps developed in the previous step served as the foundational for the development of the reference model, as illustrated in Figure 7.

The reference model represents the current state of design and serves as a baseline for future refinements. It is expressed as a high-level graphical structure composed of interconnected factors and cause-effect links. Each factor—defined as an attribute of an element that influences the object of study—can be observed, measured, or assessed. Links include the supporting source and are characterised using "+", "–", or "0" symbols to denote how the value of one factor relates to another.

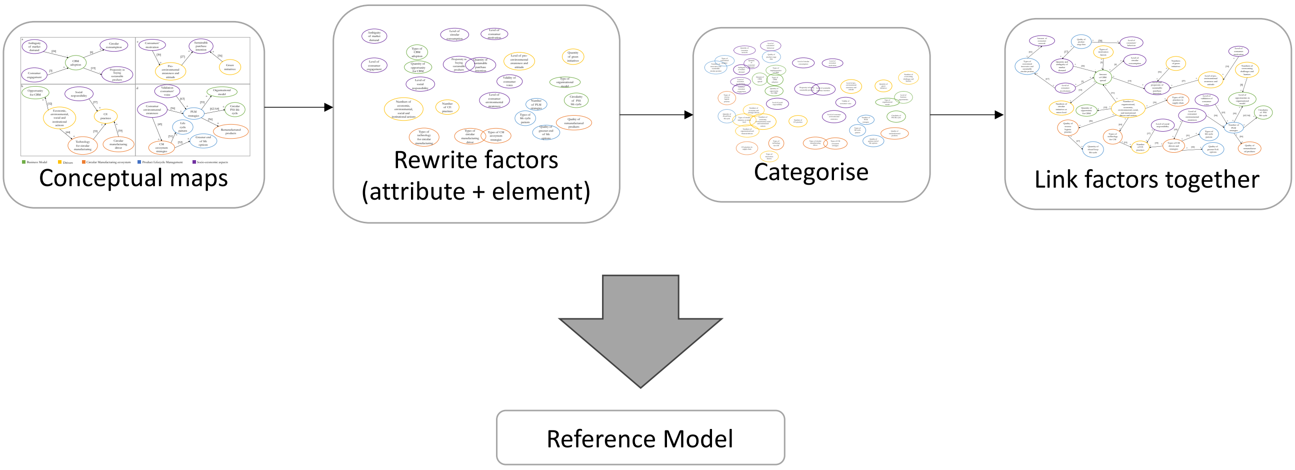


Figure 7. Scheme of the research methodology adopted.

During the model construction, factors were classified into key factors, success factors, and measurable success factors. Key factors capture the core elements shaping the system; success factors sit at the end of the causal chain and reflect the main research objectives; measurable success factors specify aspects that can be qualitatively or quantitatively assessed.

The development process began with restructuring the initial factors extracted from the conceptual maps related to the five CE-RE dimensions (Business models, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects), reformulating them as factor and attribute following DRM guidelines. Then, similar factors across maps were grouped, producing a more compact and coherent structure. The original relations were translated into new connections between the refined factors, adding symbols for the new relations and further characterizing the existing ones with the symbol on both sides of the arrows (describing the value in relation the factor's attributes).

Finally, key, success, and measurable success factors were identified, and the model was customised to highlight the different types of RE (direct, indirect, economy-wide, and transformational) using colour-coded links, based on insights from the initial conceptual maps.

3.2.3 Analysis of theoretical and practical gaps

To further examine and extend the research domain, key research gaps were identified. The same systematic literature review was used for this purpose, applying the same search queries but adopting different inclusion criteria tailored to this objective, as presented in Figure 8. A total of 65 papers were included based on their relevance in describing CE-RE dimension characteristics, highlighting inter-dimensional links, discussing performance metrics, or explicitly reporting gaps within the domain.

The research gaps extracted from these papers were then analysed using the Sort, Label, Integrate and Prioritize (SLIP) methodology (Maeda, 2006), resulting in seven thematic categories: Attitudes and behaviours, Ecosystem configurations, In-depth conceptual studies, Industrial applications, Performance measurements, Policy and regulations, and Technological potential. These categories were subsequently prioritised according to their frequency within each CE-RE dimension and across the full sample.

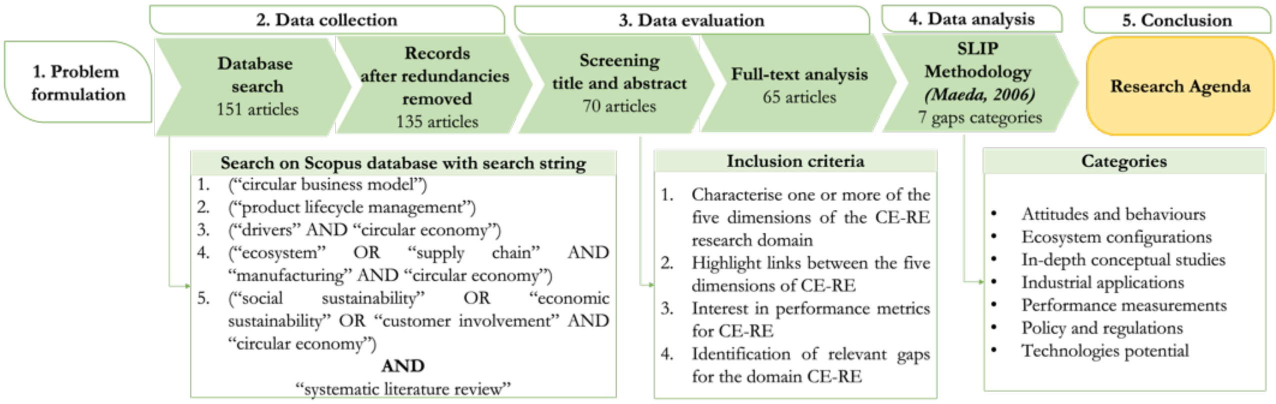


Figure 8. Research methodology overview

To complement these theoretical insights—which themselves highlight a major gap in the CE-RE research domain—and to assess whether companies implementing CE strategies are aware of potential negative consequences, a set of semi-structured interviews was conducted.

Three companies were selected for the interview. These companies within the automotive industry were involved in the production of different parts of the car, including tyres, the design of the whole car, and specific components. These different perspectives provided a global insight into the adoption of CE practices in the automotive industry. Following a predefined protocol, three separate semi-structured interviews were conducted online, involving at least one person from the company involved.

The interview protocol is based on six questions addressing the CE transition in the company, which are reported below:

1. Interviewees profile and information: question aiming to understand the role of the interviewees in the company and his involvement in pursuing a circular transition.
2. Company information about CE: question aiming to understand the company's already put-in-place actions and activities for achieving a circular transition.
3. Circular strategies adopted: question aiming to explore the circular strategies already implemented in the company.
4. Benefits achieved: question aiming to identify the benefits obtained after the adoption of circular strategies.
5. Methods to capture circular benefits: question aiming to understand whether and how the benefits obtained from the implementation of circular strategies are measured.
6. Negative effects detected: question aiming to explore the negative consequences (or at least the related companies' awareness) due to the implementation of circular strategies.

In Table 6, information about the single interviews is reported.

Table 6. Interviews details

Automotive company	Employee role	Interview duration	Interview date
A	Mechanical Department Manager	25 min	2024/02/19
B	Environmental Innovation Manager	25 min	2024/02/20
C	Power Department	20 min	2024/03/04

3.3 Stage 3: Prescriptive Study

The third DRM stage, *Prescriptive Study*, aims to develop a desired situation, represented in the impact model, where the support to achieve this situation is defined and a prototype tool is subsequently developed, as illustrated in Figure 9. The impact model outlined the targeted future state and therefore included both the required support and its expected effects. Developing this model required adapting the reference model by introducing new nodes and links—such as auxiliary effects resulting from the use of the support—removing elements no longer relevant once the support is introduced, and adjusting the attribute values of selected factors.

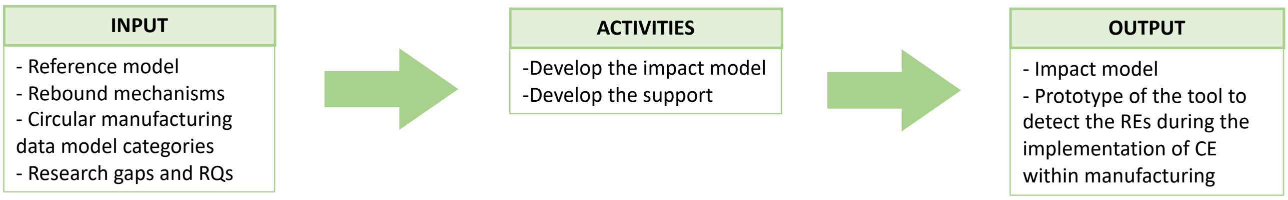


Figure 9. Stage 3: Inputs, Activities, Outputs

3.3.1 Translating the reference model into the impact model

To achieve this, the first task involved identifying the relevant factors within the reference model that reflect rebound mechanisms from the producer perspective. This stage builds directly on the key output of the previous DRM phases—the reference model (Blessing and Chakrabarti, 2009).-In that model, factors belonging to the five CE-RE dimensions (Business models, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects) were interconnected to highlight where potential REs could arise during CE implementation. While the reference model provided a structured representation of the current situation, mapping causal relationships among factors, it did not yet clarify how and why REs may emerge.

The Prescriptive Study addressed this limitation by refining the research design and identifying the factors and links most relevant for explaining RE triggers. The definition of RE mechanisms proposed by Guzzo et al. (2024) was adopted to guide the selection of the key factors and causal links, ensuring a systematic and up-to-date approach. This study was chosen due to its comprehensive and recent categorisation of rebound mechanisms. The CE-RE reference model was then analysed to identify and classify the links that aligned with these definitions, explaining how specific efficiency-oriented actions may lead to REs. During this step, factors were also distinguished as causes or effects and examined from both producer and consumer perspectives. In total, analysis of all 32 factors in the reference model resulted in the identification of 17 RE mechanisms, classified into causes and effects, providing a structured explanation of how and why REs may occur.

The subsequent step focused on detecting and categorising the links in the CE-RE reference model according to the four categories of the circular manufacturing data model (i.e., product, process, management, and technology), with the aim of determining which types of data should be collected in a CE-RE context. Although the reference model represents the causal structure of the CE-RE domain, it does not specify the data required to identify where REs may arise. To address this gap, the circular manufacturing data model (Acerbi et al., 2022) was introduced into the research design. The four circular manufacturing data categories—product, process, technology, and management—were analysed and mapped onto the links between factors in the CE-RE reference model. Each link was examined, classified, and assigned to a circular manufacturing data category, thereby identifying the data needed to support RE detection.

These two results served as the foundation for constructing the impact model. Building on the insights derived from the analysis of circular strategies and the identification of rebound mechanisms, the impact model was designed to integrate the most relevant factors and causal links needed to represent the desired situation—that is, a manufacturing system in which potential REs can be systematically detected before undermining circular outcomes. To achieve this, the model consolidates and connects the key elements that influence how REs emerge, unfold, and affect sustainability performance within circular manufacturing.

During the impact model development, additional factors were introduced to refine the representation of specific relationships that had not been fully captured in the previous stages. These supplementary factors were necessary to more accurately characterise how certain organisational decisions, process configurations, or behavioural responses may trigger rebound pathways. New causal links were also incorporated to illustrate further direct and indirect interactions among system components, thereby providing a more comprehensive depiction of the mechanisms through which REs can arise across different business processes.

A crucial component of the model is the definition of the support factor, which represents the assessment tool developed in this research. The support factor was strategically positioned within the model to indicate the points in the manufacturing system where the tool would have the greatest leverage—namely, the factors and relationships most strongly associated with RE emergence. By connecting the support factor to these critical nodes, the impact model clarifies not only where the tool should intervene but also how its use can guide companies in recognising early signals of rebound risks.

Overall, the development of the impact model translated the conceptual insights generated throughout the research into a coherent, system-oriented framework that operationalises the detection of potential REs. By clarifying the critical points of intervention and the causal pathways through which rebounds may arise, the model provides a structured foundation for systematically identifying rebound risks and supporting more informed decision-making during the implementation of circular strategies, thereby strengthening manufacturers' ability to safeguard the intended sustainability benefits of the CE transition.

3.3.2 Steps for developing the detection-driven tool

Once the support factor required to achieve the desired situation was identified, a prototype of the detection-driven tool was developed. The prototype was initially informed by a rapid review of sustainability reports from companies operating in different industrial sectors. To ensure coverage of a wide spectrum of production dynamics, the selection focused on three companies specifically on firms belonging to two major categories: discrete manufacturing (e.g., production and assembly) and continuous process. This criterion allowed the analysis to capture variations in reporting practices and sustainability challenges across fundamentally different production processes. Reports from multiple years were examined to identify recurring patterns, evolving trends, and stable information needs relevant to supporting the development of the prototype. This review aimed to identify the main sustainability objectives linked to the 17 SDGs and to understand how companies are currently incorporating circular economy principles. These insights supported the design of a tool capable of presenting and detecting potential REs in the manufacturing industry.

In addition, the results of the study examining the connections between circular manufacturing strategies and rebound mechanisms (3.1. Stage 1: Research clarification) were used as an input to determine how specific CE strategies may generate particular rebound mechanisms. Building on these insights, the tool was developed in MS Excel and structured into several interconnected spreadsheets. In total, ten sheets were created: one introducing the tool; four dedicated to SDGs, circular manufacturing strategies, rebound mechanisms, and CE assessment indicators identified in the literature; one “identity kit” for company information; one qualitative questionnaire with its corresponding data collection sheet; and a final sheet for additional notes or information.

The CE indicators were first identified using the results obtained in methodology 3.1 Stage 1: Research Clarification. To enrich the analysis with more practice-oriented indicators, two major circular assessment frameworks proposed by Saidani et al. (2018) and Kravchenko et al. (2020) were then incorporated. In addition, the micro-level indicators were derived from the literature review conducted by proposed by have been added, while the micro-level indicators were derived from a literature review conducted by Vinante et al. (2021). All identified indicators were subsequently linked to circular strategies and rebound mechanisms based on the specific aspects they are designed to measure or assess.

The four informative spreadsheets compile lists of elements, such as the SDGs, circular manufacturing strategies, rebound mechanisms, and CE assessment indicators, along with their respective definitions. The qualitative questionnaire was structured as follows: an initial set of questions explores the sustainability goals the company is pursuing and the circular strategies implemented to achieve them. This is followed by a series of questions designed to assess whether specific actions may be generating REs. For each rebound mechanism, two targeted questions are included, each linked to key variables representing distinct aspects of that mechanism.

3.4 Stage 4: Descriptive Study II

The final DRM stage, *Descriptive Study II*, focuses on evaluating the developed methodology (Figure 10). This phase includes a theoretical and empirical verification through expert consultation to assess the method's reliability, applicability, and effectiveness, with the aim of gathering feedback and suggestions for improvement.

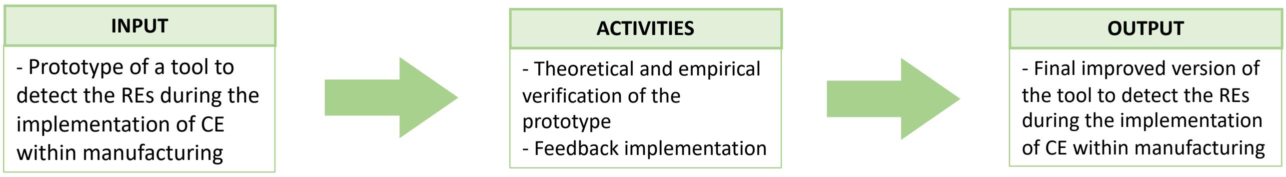


Figure 10. Stage 4: Inputs, Activities, Outputs.

The theoretical evaluation through expert consultation consisted of a series of meetings in which the tool was presented, along with its objectives and intended use. During each meeting, the tool was shared with the expert to allow hands-on exploration of all its components. This interaction enabled the collection of spontaneous feedback on how the tool is designed to support the detection of REs during the implementation of circular strategies in manufacturing, as well as on its usability and its ability to provide valuable data and insights.
This process allowed the identification of qualified experts capable of evaluating the results of the PhD project. The selected experts were contacted via email and invited to contribute to the evaluation of the research project through an online meeting. Academic experts were chosen based on their main areas of expertise relevant to the study, they were selected through an analysis of the authors featured in the publications identified in the systematic literature review:

- Adriana Hofman Trevisan (Polimi, 3-5 years of experience, circular economy ecosystem)
- David Font Vivanco (IRTA – CREDA, 10 years of experience, circular economy rebound)
- Benjamin H. Lowe (University of Sheffield, 10 years of experience, ecological economics)
- Daniela C.A. Pigosso (DTU; more than 10 years of experience; design for absolute sustainability)
- Daniel Guzzo (DTU; 10 years of experience; system dynamics)
- Veronica Arioli (UniBG, 3-4 years of experience, servitization)
- Janaina Mascarenhas (USP, more than 10 years of experience, circular economy)
- Camila G.C. Castro (IFMG, more than 10 years of experience, circular economy ecosystem)
- Rob Vingerhoeds (ISAE – SUPAERO, more than 10 years of experience, system engineering)
- Federica Acerbi (Polimi, 5-8 years of experience, sustainable manufacturing)
- Mélanie Despeisse (Chalmers University of Technology, more than 10 years of experience, industrial sustainability)
- Stella Viscardi (Polimi, 3-5 years of experience, circular supply chain)

- Fabiana Tornese (Università del Salento, more than 10 years of experience, industrial system engineering)

Nine experts replied to the email: Adriana Hofman Trevisan; David Font Vivanco; Benjamin H. Lowe; Daniela C.A. Pigosso; Daniel Guzzo; Veronica Arioli; Camila G.C. Castro; Federica Acerbi; and Stella Viscardi. The interviews were conducted online between January and February 2026, each lasting approximately 30–60 minutes. At the beginning of each interview, a brief overview of the research objectives and the specific gaps the tool aims to address was presented. This introduction was followed by a demonstration of the tool, describing its overall structure, the purpose of each sheet, and the logic underpinning its functioning. After this guided walkthrough, the tool was shared directly with the experts, enabling them to navigate it autonomously and explore its features in depth. This hands-on interaction was essential to facilitate precise, practice-oriented, and methodologically grounded feedback.

The insights collected from the interviews were systematically analysed to consolidate expert suggestions, evaluate their relevance, and identify those most beneficial for the final verification of the tool. Each expert provided contributions informed by their professional expertise—ranging from CE research, industrial sustainability, and business model innovation to resource efficiency and organisational decision-making. These diverse viewpoints offered complementary reflections on the tool's potential to advance academic knowledge, support industrial practice, and strengthen organisational awareness of REs in circular manufacturing. The analysis focused on identifying areas of convergence, complementarity, and divergence in expert opinions to assess the overall coherence of the feedback. Additionally, each recommendation was evaluated in terms of technical feasibility, methodological soundness, and alignment with the intended purpose of the tool, thus determining whether it could be integrated into the final version.

Developing a tool capable of detecting the potential occurrence of REs during CE implementation in manufacturing represents a highly complex and iterative endeavour.

During the interviews, experts evaluated the quality, clarity, and relevance of the information included in the tool, such as the selected CE strategies, the scientific validity of the rebound mechanisms, and the relevance of integrating the SDGs into the tool. They were invited to comment on whether the tool's structure was logical and intuitive, whether the relationships among CE strategies, rebound mechanisms, and SDGs were clearly represented, and whether the tool could realistically support decision-making processes in manufacturing companies. Additional questions explored potential barriers to adoption, missing elements, and opportunities to enhance usability and applicability.

All interviews were transcribed and analysed qualitatively. A thematic analysis was performed to identify recurring observations, points of agreement, and divergent views. Insights from this analysis informed targeted refinements of the tool and contributed to assessing its readiness for future real-world application. Participation was voluntary, and all experts were informed about the exclusive research use of the collected data.

Through this protocol, the interview process ensured a systematic and rigorous assessment of the tool, grounding its development in both theoretical knowledge and practical expertise. While the interactive development approach contributed to embedding empirical insights into the tool, experts emphasised that its ultimate validation will depend on widespread application in industrial settings. Only through longitudinal use and continuous refinement informed by practical experience will the tool's full effectiveness and relevance be confirmed.

Taken together, the expert assessments confirm that the tool offers a comprehensive and meaningful knowledge base capable of supporting both research and industry practice in the CE–RE domain.

The empirical validation of the detection-driven tool was conducted through a structured protocol involving consultation sessions with industrial experts. Two consultation sessions were organised with industrial experts selected from companies operating in the local territory, primarily within the parts production and assembly sectors—industries directly relevant to the focus of this thesis and previously analysed through their sustainability reports. The selection criteria prioritised professionals directly involved in sustainability-related activities or holding strategic decision-making roles, ensuring that the feedback reflected practical needs and operational realities of manufacturing contexts. Industrial experts were contacted based on their role in the industry relevant to the study:

- Expert 1: Health, Safety and Environment Manager;
- Expert 2: Energy Manager;
- Expert 3: Facility Manager.

Each session followed a consistent format and began with a short introductory presentation outlining the definition of CE within manufacturing, followed by an explanation of REs, illustrated through practical examples and specific cases showing how rebound mechanisms may emerge within industrial plants. The introduction also emphasised why recognising and addressing REs has become an urgent priority for companies pursuing circular strategies.

Following this contextual introduction, the detection-driven tool was presented in detail. The overall structure and the purpose of each spreadsheet were explained, and the experts were guided through the tool's workflow to ensure a clear understanding of its logic, underlying assumptions, and intended functionalities. This walkthrough served as a basis for the subsequent evaluation phase. In the final part of each meeting, an open feedback session was conducted, during which experts were encouraged to comment on the clarity, usability, and relevance of the tool, as well as its potential integration into existing corporate processes. Each consultation lasted approximately 30–60 minutes.

To structure the discussion and support consistency across interviews, the evaluation was guided by key thematic questions addressing the following aspects:

- Overall impressions of the tool, including clarity, completeness, and perceived usefulness.
- Conceptual soundness, focusing on the appropriateness of the CE strategies, RE mechanisms, and SDG integration.
- Structure and usability, such as the intuitiveness of the workflow and the clarity of the relationships among CE strategies, rebound mechanisms, and expected outcomes.
- Practical applicability, including whether the tool could realistically support decision-making in manufacturing contexts and what barriers might hinder adoption.

- Opportunities for improvement, such as missing elements, additional examples, or adaptations needed for industrial use.

The interviews were conducted in a workshop style format to encourage interaction and to allow the involvement of a larger number of company representatives to share their perspectives. The comments and suggestions collected during the sessions provided several valuable insights to enhance the applicability of the tool in real projects. All feedback received was systematically analysed and used to refine and improve the tool, with the aim of increasing its clarity, coherence, and overall usability for real-world industrial applications.

4. Results

This section presents the results generated across the different stages of the methodology. For clarity, the outcomes are organised according to the four main research stages. The results can be summarised as follows:

- *Research Clarification*: identification of where REs emerge during the implementation of circular strategies in the manufacturing industry, and an initial understanding of the mechanisms through which these REs are triggered, including a systematic review of CE performance assessment methods.
- *Descriptive Study I:* in-depth analysis of the current dynamics explaining where and how REs occur, the development of the reference model, and an exploration of practitioners' level of awareness regarding REs.
- *Prescriptive Study*: definition of the desired situation, represented through the impact model, followed by the development and presentation of the first prototype of the tool.
- *Descriptive Study II:* validation of the tool through expert assessment and feedback.

4.1 Results from Stage 1: Research Clarification

This section presents the three main results from the first stage of the DRM, *Research Clarification*.

4.1.1 Investigating the rebound effects of circular economy in manufacturing

The first result obtained was related to understand where REs occur during the adoption of CE within manufacturing. The systematic literature review conducted led to the selection of 34 publications cover a time period from 2015 to 2023. The trend of publications increases in the years (2021 and 2022), when achieved respectively 21% and 38%. Analysing the authors' nationality, the highest number of contributions come from European countries (Denmark, Italy, Netherlands, and Sweden), followed by Brazil and United States. The composition of the 34 contributions in terms of types of documents is as follows: 31 journal articles, 2 papers in proceedings of scientific international conferences, one book chapter, and one editorial. The journals contributing to the research domain with a higher number of contributions are *Journal of Cleaner Production* and *Journal of Industrial Ecology*. In terms of research method adopted, most of the analysed papers (19 out of 34) provide a theoretical assessment on CE and RE. 5 contributions present an analytical method to study the link between the two topics within manufacturing. 6 papers provide theoretical research followed by an application case (almost ever in the manufacturing sector). 3 contributions implemented case studies in three different industries (manufacturing, textile and electronic). Only one paper provided a survey about the consumers' role in CE related to RE within manufacturing.

Analysing the 34 contributions selected, five dimensions were detected: Business model, Drivers, Circular manufacturing ecosystem, Socio-economic aspects, and PLM, details of the selected contributions are provided in Table 7. Together, these dimensions provide a structured lens to examine how and where CE strategies interact with REs in manufacturing.

Table 7. Analysis of the selected contributions

Dim.	Ref	Content	Industry	RE dim.	Gap
BUSINESS MODEL	(Liu et al., 2022)	CE's RE investigated through a new business model to extend the lifetime of clothing	Textile	Env	Focus on biodiversity and CE
	(Koide et al., 2022)	Life cycle assessment (LCA) applied to PSS, analysing different scenarios to find CE strategies that show the level of backfiring risk.		Env	Investigate the publication biases and methodological differences in CE methods.
	(Kjaer et al., 2019)	PSS framework and CE strategies are evaluated through requirements to achieve absolute resource decoupling.	Textile	Env, eco	Business context isn't evaluated enough
	(Kjaer et al., 2018)	In PSS, it's developed a set of guidelines, where three profiles are considered	Mobility	Env, design	Need of supplementary methodology
	(Widmer et al., 2018)	PSS aligned with CE, with a focus on design of supply chain and mitigating RE.	Mobility	Env, ene	Supply chain to affect value creation
	(Salvador et al., 2020)	Circular business model participates in the CE transition, fostering remanufacturing.		Env, eco	Circular business model neglects the social aspect.
	(De Pádua Pieroni et al., 2018)	The criteria identified sustainability characteristics in business models based on social, environmental and economic.		Env, ene, design	The criteria are conceptual by nature and require validation in practice.
	(van Loon et al., 2021a)	The knowledge about CE perspective is mapped focusing on circularity and gaps.		Env, ene	The use of environmental performance
	(Ryen et al., 2022)	Historical precedents of CE models are the theoretical base to achieve transition in practice in multiple fields.	Food, electronic	Env, eco, design	Different fields to analyze the transition
	(Chen, 2021)	CE's RE is analyzed through social justice and environment in sustainable cities.		Env, ene	Environmental degradation impact.
DRIVERS	(Metic and Pigosso, 2022)	A systematic literature review investigates RE in CE through five disciplines. Triggers and drivers are individuated in the disciplines		Env, ene, eco	A lack of approaches to measure and anticipate the potential magnitude of RE.
	(Zerbino, 2022)	To manage CE rebound four guidelines are developed.	Marble	Env	Guidelines to be used in PSS context.
	(Font Vivanco et al., 2022)	A series of criteria are identified and evaluated to characterize RE.		Env	RE research-behavioral science interaction
	(Castro et al., 2022)	Framework on the mechanisms that lead to RE in CE.		Ene, eco	Lack of empirical data
	(Zink and Geyer, 2017)	Factors causing CE rebound are outlined, with appropriate preventative measures.		Ene	Unpredictable nature (complex system)
	(Morseletto, 2022)	Sustainability studied through environmental principles (favors sustainable practice).		Env	Lack of knowledge of the impacts
	(Camana et al., 2021)	The waste management in Italy is explored by different tools in relation to RE		Env, eco	Similarities and discrepancies.
	(Siderius and Poldner, 2021)	Qualitative research methodology investigates RE in CE system.	Textile	Env, eco	Lack of education on the RE phenomenon
	(Bressanelli et al., 2022)	The smart CE paradigm as is defined and conceptualized, due to digital technologies.		Env	Set of digital technologies is pre-defined.
	(Bertassini et al., 2022)	Fuzzy Delphi Methodology approach is evaluated to implement a CE-oriented culture, that may contribute by mitigating possible RE	Mining, steel	Env, eco	Different fuzzy information to deal with hesitations in the subjective judgments

	(Figge and Thorpe, 2019)	Benefits and two contributions from symbiotic rebound are discussed: expansion of knowledge on RE, and the development of theory on the CE.		Env, eco	The empirical research could determine the impact and scope of imperfect information.
CIRCULAR MANUFACTURING ECOSYSTEM	(Vegter et al., 2023a)	Interdependences between dynamic nature and performance aim result in causes and effects that offer several pertinent benefits.	Manufacturing	Env, ene	The interdependencies have different nature.
	(Lombardi and Cembalo, 2022)	Consumers' role is important in the transition towards CE: the consumers have the power to decide between a one made up of virgin or recycled materials.		Eco	The challenge is determined by human need
	(Wiprächtiger et al., 2022)	Treat the environmental and energetic assessment to prevent municipal solid waste.	Textile, furniture	Env	Identifying the diffusion factors is an issue.
	(Laurenti et al., 2016)	The eco-innovation policies are focused on reducing the RE and promoting sustainable consumption patterns.		Env	PSS must be combined with environmental policy, such as externality taxes.
SOCIO-ECONOMIC ASPECTS	(Safarzynka et al., 2023)	A novel model of CE is applied to four recycling scenarios to prevent RE	Manufacturing	Ene	CE transition: fiscal/monetary policy role
	(Flores et al., 2022)	A design approach is proposed to define Energy Sustainability functions and identify couplings that create rebounds in domains.		Ene	A second and additional levels define the policy for a country, region, or enterprise
	(Niero et al., 2021)	Analytic approaches are used to analyse CE initiatives in socio-technical systems.	Manufacturing	Env	Unintended side effects due to LCA .
	(Skelton et al., 2020)	The greenhouse gas emission RE is examined across a efficiency scenarios.	Automotive	Env, ene	Surpluses could minimize RE
	(Makov and Font Vivanco, 2018)	Two rebound mechanisms are evaluated in smartphone reuse, which may counteract the environmental benefits of CE strategies	Electronic	Env, ene, eco	The first user might underestimate the impacts of the products' second life.
PRODUCT LIFICYCLE MANAGEMENT	(Levanen et al., 2021)	Environmental impact of textile waste and potential benefits of innovative recycling compare global warming potential in five ownership and end-of-life scenarios	Textile	Env	Implications for other sustainability dimensions outside must be investigated.
	(Bakker et al., 2021)	three topics: product design, circular business model, environmental & economic impact assessment.		Design	Lack of empirical validation and evaluation
	(Laurenti et al., 2015)	Identified the challenges to sustainability in the design of electronic products.	Electronic	Env, ene,design	There is a lack of indicators
	(Birat, 2015)	The CE concept meaning is proposed by the standpoint of materials stakeholders and how it can be refined with a practical approach.		Env	Efficiency and geopolitical resource not always equate to reduce footprint.

The Business Model dimension focuses on organizational strategies—often PSS-based—used to create value through CE practices. Models such as PSS (Kjaer et al., 2019; Koide et al., 2022), circular PSS with supply chain design implications (Widmer et al., 2018) and three environmental performance strategies (Kjaer et al., 2018), and circular business models (De Pádua Pieroni et al., 2018; Ryen et al., 2022) influence resource reduction, product lifetime extension, and environmental performance, while also potentially triggering REs, as observed in reuse (van Loon et al., 2021a) and remanufacturing contexts (Salvador et al., 2020) and even in sustainable cities (Chen, 2021).

In the textile industry, innovative business models also shape the relationship between risk, money and time (Liu et al., 2022).
The Drivers dimension investigates the triggers and mechanisms that fuel or accelerate REs, drawing on insights from fields such as energy and ecological economics, socio-technological studies, sustainability, and industrial ecology (Metic and Pigosso, 2022). Research highlights the need to identify key mechanisms (Castro et al., 2022; Font Vivanco et al., 2022), manage and prevent REs (Zerbino, 2022; Zink and Geyer, 2017), consider environmental principles (Morseletto, 2022), and address environmental impacts generated by waste management (Camana et al., 2021), supported by digital technologies as key mitigation enablers (Bressanelli et al., 2022). The role of REs within the CE transition has also been explored from systemic and symbiotic perspectives (Figge and Thorpe, 2019; Siderius and Poldner, 2021).
The Circular manufacturing ecosystem dimension analyses interdependencies among supply chain actors, evaluating upstream and downstream relationships, performance objectives, and the dynamic nature of manufacturing ecosystems to identify CE benefits (Vegter et al., 2023a), including the central role of consumers in CE transitions (Lombardi and Cembalo, 2022) and the importance of waste prevention for environmental impact reduction (Wiprächtiger et al., 2022). Eco-innovation policies further shape sustainable production and consumption patterns in manufacturing (Laurenti et al., 2016).
From a socio-economic perspective, presented in the Socio-economic dimension, research examines how macro-level factors—such as raw material recycling (Safarzynka et al., 2023), system coupling to investigate four adjacent domains (Flores et al., 2022), socio-technical dynamics (Niero et al., 2021), and greenhouse gas emissions across sectors including automotive (Skelton et al., 2020) and electronics (Makov and Font Vivanco, 2018)—can generate or amplify REs.
Finally, the Product Lifecycle Management dimension investigates information flows, design approaches, and end-of-life processes that influence circularity across the product lifecycle, including recycling evaluations (Birat, 2015; Levanen et al., 2021), design-for-X strategies (Bakker et al., 2021), and environmental impacts associated with extending product lifetimes in sectors such as electronics (Laurenti et al., 2015).
Collectively, these five dimensions provide a comprehensive initial framework for systematizing the intertwined dynamics between CE strategies and REs in manufacturing.

4.1.2 Overview of potential rebound mechanisms activated by circular strategies

The second result obtained in the first stage of DRM regards how CE strategies implemented in manufacturing trigger rebound mechanisms.
The first result obtained is that categorises circular manufacturing strategies according to the Circular Strategy Scanner across the four key business processes: business model, production, product design, and procurement (Table 8).

Table 8. Circular manufacturing strategies according to the Circular Strategy Scanner and applied across business processes

BUSINESS PROCESSES	CIRCULAR STRATEGY SCANNER			
	Rethink and reconfigure	Restore, reduce and avoid	Recirculate parts and products	Recirculate materials
Business model	Circular business model or PSS/servitization			
Production		Lean production or cleaner production Material and energy efficiency	Waste management	Waste management
Product design		Circular design practices	Remanufacturing Reuse Disassembly	Recycling
Procurement	Close-loop supply chain and reverse logistics	Close-loop supply chain	Close-loop supply chain	Industrial symbiosis and eco-industrial park

In the Business Model process, circular business models—particularly PSS—fall under the "Rethink and reconfigure" category, as they fundamentally redefine how value is created, delivered, and captured. In practice, PSS models shift ownership from consumers to providers, extend product lifespans, and decouple revenue from material throughput. A well-known example is Rolls-Royce's "power-by-the-hour" model, which delivers engine functionality rather than the engine itself (Tukker, 2015).

In Production, circular strategies span multiple categories of the Circular Strategy Scanner. The first, "Restore, reduce and avoid," focuses on process-level optimisation to minimise resource use, emissions, and waste generation. Examples include lean and cleaner production—such as Toyota's lean manufacturing system, which systematically reduces inefficiencies across workflows (Womack and Jones, 1997) —and material and energy efficiency initiatives, exemplified by Siemens' use of internet of things enabled systems to monitor and optimise real-time resource consumption (Porter and Heppelmann, 2014). The remaining categories, "Recirculate parts and products" and "Recirculate materials," involve recovering the residual value of components and materials through waste management and closed-loop systems. For instance, in HP's closed-loop programme, nearly all components of ink and toner cartridges are recovered, reused, or recycled, ensuring that materials re-enter new production cycles rather than being landfilled. Together, these strategies enhance resource efficiency, support material recirculation, and reinforce circular flows within manufacturing processes.

In the product design process, circular manufacturing strategies span three Scanner categories. Circular design practices within "Restore, reduce and avoid" aim to minimise resource use and enable future interventions such as repair or remanufacture (e.g., Fairphone's modular smartphones). Strategies like remanufacturing, reuse, and disassembly fall under "Recirculate parts and products", extending component lifespans across product cycles (e.g., Caterpillar's remanufactured engine parts or Dell's design for disassembly). Finally, recycling—classified under "Recirculate materials"—targets material-level recovery and reintegration into new production, as seen in BMW's use of recycled aluminium and plastics.

In procurement, circular strategies span multiple Scanner categories. Closed-loop supply chains and reverse logistics primarily align with "Rethink and reconfigure," as they involve fundamental changes in how materials and products are sourced, delivered, and returned. These strategies also intersect with "Restore, reduce and avoid" and "Recirculate parts and products," reflecting their multifunctional role in enabling circular flows. Examples include Xerox's take-back and refurbishment programs and major retailers like Amazon that operate extensive reverse logistics systems.

Industrial symbiosis and eco-industrial parks fall under "Recirculate materials," as they foster the exchange of materials, energy, water, and by-products among industrial actors. A prominent example is the Kalundborg Industrial Symbiosis, where companies repurpose waste streams as inputs for other processes, thereby preserving material utility across organizational boundaries.

Mapping circular strategies across these processes provides a framework to identify how and where companies can implement CE strategies, clarifying the objectives supported by each approach. Subsequently, each strategy was linked to potential rebound mechanisms, illustrating how efficiency gains and circular practices can unintentionally trigger negative effects in manufacturing.

In the following tables, the strategies are organized by business process, along with the associated rebound mechanisms and related illustrative examples. It is interesting to note that, across the various examples, the same input (e.g., increased efficiency) may lead to the same effect (e.g., increased production, increased resource use) through different mechanisms, each capturing a distinct causal dynamic.

Table 9. Rebound mechanisms triggered by the CE strategies in business model process.

Circular strategies in Business model	**Rebound mechanisms**	**Examples**
Circular business model or PSS/servitizazion	Price	*A company adopts a circular business model to reduce the use of raw materials, but the reduce costs allow the company to produce more units at a lower price, leading to an increase in consumer demand.*
	Re-investing	*A company adopts a circular business model to reduce the use of raw materials and lowering production costs, but the company reinvests these savings into expanding its product line.*
	Market price	*A company reallocates budget in adopting a PSS solution for machinery, but the reduced price encourages the company to invest in additional machinery, leading to higher overall sales.*
	Sufficiency	*The introduction of a circular business model reduces the company's overall material demand. However, competitors seize the opportunity to fill the market gap by offering cheaper, less durable alternatives. As a result, overall consumption remains high, offsetting the intended resource savings.*
	Demand adjustment with investment adjustment	*An electronics company integrates a refurbished smartphone program into its circular business model, improving material efficiency. Lower production costs reduce the price of refurbished devices, making them more attractive to consumers. This increased affordability stimulates higher demand, ultimately leading to greater overall consumption*
	Moral licensing	*I adopted circular business model, so I am justified in increasing production volume*
	Time discounting	*The adoption of circular business model is a long-term solution, so the company decides to implement it later*

The implementation of circular strategies within the business model process (Table 9)—particularly circular business models and PSS—can trigger several rebound mechanisms. Five originate from producer-side dynamics, while two stem from behavioural mechanisms typically associated with consumers but also relevant in corporate decision-making.

From the producer's perspective, circular business models and PSSs are generally introduced to reduce raw material use and improve resource efficiency. However, these strategies may unintentionally generate REs. For example, reducing production costs through circular business model adoption can lower product prices, stimulating consumer demand and production volumes, ultimately increasing resource consumption. This dynamic reflects the price rebound mechanism, where efficiency gains are undermined by demand-side reactions to reduced costs.

Additionally, when companies achieve cost savings through circular business model implementation, they may reinvest these savings into expanding product lines or scaling other operations, not all of which align with sustainability goals. Such reinvestment can increase the overall environmental impact despite initial efficiency benefits, reflecting capital reallocation within the firm. Similarly, improvements in product or service efficiency—common in PSS adoption—can make technologies or services more accessible and affordable, generating broad demand-side reactions. This may encourage firms to expand their asset base, such as by acquiring additional machinery, thereby driving up production and resource use—an effect aligned with the market price mechanism.

Another relevant mechanism concerns sufficiency. Circular business models aim to reduce material throughput and promote more sustainable consumption. However, when one company reduces its material demand, competitors may respond by filling the perceived market gap with cheaper, lower-quality alternatives. In such cases, total consumption may remain unchanged or even increase, negating the resource savings achieved by the initial circular business model adopter.

A similar paradox arises when lower production costs due to circular business model adoption lead to reduced market prices. Although this increases access to more sustainable goods, it may also trigger additional consumption through market-wide reactions. For instance, offering refurbished electronics at lower prices can boost demand to the point where total material usage increases, despite the greater circularity of the products. In these cases, both demand and investment adjustments combine to trigger REs that contradict circularity goals.

While these mechanisms are predominantly production-oriented, behavioural mechanisms—commonly described at the individual level—can also emerge during circular business model implementation. The moral licensing mechanism plays a role when companies perceive their sustainable initiatives as a justification for engaging in more resource-intensive practices elsewhere. Although typically associated with consumers, the same logic can apply to corporate decisions, where an initial circular initiative legitimizes actions that counteract sustainability. Similarly, time discounting, where long-term sustainability benefits are undervalued relative to short-term economic gains, can lead firms to delay or deprioritize circular strategies despite acknowledging their future advantages.

Overall, the examples included in the Table 9provide valuable insights into how REs can emerge during circular business model implementation. They highlight how interactions among economic incentives, competitive responses, and behavioural tendencies can reduce or even cancel out the expected environmental benefits of circular business model and PSSs.

Table 10. Rebound mechanisms triggered by the CE strategies in production process

Circular strategies in Production	Rebound mechanisms	Examples
Lean production or cleaner production	Structural change	*A factory adopts water-efficient technologies but expands production due to cost savings, resulting in an overall increase in total water consumption.*
	Time	*A company adopts lean production techniques, streamlining processes and reducing downtime. As a result, production speed increases, allowing the company to produce more units in the same timeframe. This leads to higher overall resource consumption.*
	Producer-induced demand adjustment	*A company adopts a cleaner production process by using recycled plastics to reduce the demand for raw plastic. As demand declines, the market price of raw plastic drops, making it more affordable for other industries. This lower cost encourages new applications or increased use by other companies, ultimately leading to higher overall plastic consumption.*
	Cross-factor	*A factory upgrades its machinery to improve energy efficiency, reducing electricity consumption per unit produced. However, the enhanced in production factor also increases labour productivity, leading to higher wages and greater output. This higher output drives increased raw material consumption, offsetting some of the energy savings.*
	Social acceleration	*Technological efficiency improvements increase the production and consumption, accelerating the 'speed of life' and social change*
Material and energy efficiency	Resource market	*A manufacturer adopts energy-efficient in production, reducing the production costs and offers the product at a more competitive price in the market, leading to higher overall production and, increased energy consumption across the industry.*
	Consumption efficiency	*A manufacturing company upgrades its machinery to reduce energy consumption for production. The resulting cost savings allow the company to expand operations and produce more goods. As a result, total energy consumption increases despite the improved efficiency*
	Cross-factor	*A textile factory improves resource efficiency by adopting a water-saving dyeing process. The efficiency gains lower production costs, enabling the company to invest in automation. This increases labour productivity and production speed, leading to greater overall material use and energy consumption.*
Waste management	Resource market	*A company invests in advanced recycling technologies, making the processing of waste materials more efficient and cost-effective in the market. The company reduces the cost of waste management services for its clients, encouraging them to increase their production or consumption of goods that generate more waste.*
	Consumption efficiency	*A waste management program is introduced in a company, that improves efficiency in handling waste. As a result, production and consumption increase, leading to more purchases and waste generation than initially intended*
	Cognitive dissonance	*The adoption of a waste management program serves as an excuse for increased raw material use during high production, as companies justify their actions by producing less waste overall.*

The circular manufacturing strategies applied within the production process, the rebound mechanisms they may trigger, and illustrative examples of how these mechanisms can emerge are presented in Table 10. Overall, the table highlights how efficiency-oriented circular manufacturing practices can unintentionally generate systemic responses that reduce or even negate their expected environmental benefits.

When lean or cleaner production techniques are implemented, several producer-side REs may arise. Structural change can occur when cost savings from efficiency improvements are reinvested into expanding production capacity, often toward solutions with higher overall resource use. For instance, a factory adopting water-efficient technologies may achieve financial savings but subsequently scale operations, ultimately increasing total water consumption. Here, the RE stems not from the technology itself but from the economic response to efficiency gains, driven by the motivation to maximize output and exploit new opportunities.

Similarly, the time-based mechanism becomes relevant when lean production reduces downtime and accelerates processes. Although improved efficiency is desirable, it may lead to higher total output within the same timeframe, intensifying the use of energy, materials, and other inputs. Higher operational efficiency often incentivizes higher throughput, even when it counteracts resource-saving goals.

Producer-induced demand adjustment represents another important RE. When a company adopts cleaner production—such as substituting virgin plastic with recycled plastic—its reduced demand for primary materials may lower market prices. These lower prices can then stimulate increased consumption in other industries, potentially resulting in higher overall plastic use. This mechanism illustrates how improvements made by a single producer can trigger unintended market-wide effects.

A cross-factor mechanism arises when efficiency improvements in one production factor influence others. For example, upgrading machinery to improve energy efficiency may also increase labour productivity and output. While beneficial in isolation, this can increase total material and energy consumption, weakening the environmental benefits gained from energy savings. In interconnected production systems, such ripple effects are common and can generate complex or even contradictory outcomes.

Beyond producer-side mechanisms, behavioural dynamics also play a role. Social acceleration reflects cultural and economic pressures to produce and consume more, faster. Even when cleaner production methods are introduced, these pressures may push companies to scale operations, reinforcing a “faster is better” paradigm and undermining potential sustainability gains.

Material and energy efficiency strategies present similar rebound risks. Efficiency improvements reduce production costs and prices, making products more competitive. However, these lower prices can stimulate increased demand across entire sectors, driving total resource consumption upward. This dynamic is tied to resource market effects and the economic logic of competitiveness and growth. Moreover, efficiency gains may enable reinvestment in automation and expanded capacities, triggering consumption efficiency rebounds, where doing “more with less” ultimately results in doing much more overall.

Even waste management strategies, often perceived as inherently positive, are not immune to REs. Advanced recycling technologies may reduce the cost of waste processing, lowering the perceived environmental burden of production. As a result, companies or their clients may feel justified in increasing output. Improved waste-handling efficiency may also incentivize higher production and purchasing, ultimately generating more waste. These dynamics reflect both market-driven and consumption-efficiency mechanisms.

Finally, behavioural mechanisms such as cognitive dissonance can further complicate outcomes. When a company implements a waste management program, it may use this positive action to justify resource-intensive behaviours elsewhere—such as increasing raw material use or scaling production. The psychological comfort associated with having taken a “green” step can obscure the negative consequences of subsequent actions. This highlights the importance of addressing human and organizational behaviour alongside technical improvements.

Recognising these mechanisms is crucial for designing effective circular manufacturing strategies. Without accounting for economic incentives, market responses, and organisational behaviour, well-intended efficiency improvements may fall short or even exacerbate environmental pressures. The examples therefore serve as important signals for anticipating REs and integrating mitigation measures early in strategy development.

Table 11. Rebound mechanisms triggered by the CE strategies in product design process

Circular strategies in Product design	Rebound mechanisms	Examples
Circular design practices	Redesign	*A company designs modular and repairable products, but consumers replace or modify their furniture more frequently, increasing material demand.*
	Consumption efficiency	*A company designs modular and repairable products, consumers replace parts instead of buying entirely new products, start purchasing more units to upgrade multiple or to expand their product range, as a result, the overall demand for resources increases*
	Negative association	*I don't think that the circular design practices could generate the same level of quality, I will continue the old practices*
	Response efficacy	*A fashion brand adopts circular design practices by creating clothes from recycled materials and promoting them as a sustainable alternative. This increases production and consumption*
Remanufacturing	Imperfect substitution	*A company adopts a remanufacturing strategy, but the remanufactured products are of slightly lower quality than new ones, leading to a reduced lifespan and an increase in primary production as consumers replace them more frequently*
Reuse	Substitution	*A company implements a reuse strategy, where the costs for reused products are lower than those for new items, leading consumers to buy more reused goods and additional products*
	Single-action bias	*The adoption of reuse strategy is enough, therefore I don't have to adopt other circular solution*
Disassembly	Composition	*A company adopts a disassembly strategy, and the cost reduction allows the company to lower product prices, stimulating higher demand from consumers.*
Recycling	Consumption efficiency	*A manufacturing company adopts a recycling program to reuse scrap materials, leading to higher energy consumption and more waste being processed than originally anticipated.*
	Contributions ethics	*I already adopt a recycling program, so I don't have to implement other circularity strategies.*

In the product design process (Table 11), several circular manufacturing strategies may trigger different types of REs, driven both by producer actions and by behavioural responses. As such, even well-designed interventions may fail to deliver their expected sustainability benefits if these dynamics are not anticipated and managed.

Circular design strategies—such as modularity, repairability, and upgradability—aim to extend product lifespans and reduce material throughput. However, they can also generate unintended REs. For example, redesigned products that allow frequent upgrades or reconfigurations may encourage greater feature expansion and product turnover. Consumers may replace or modify modular furniture or electronics more often due to flexibility and perceived novelty, stimulating overconsumption rather than reducing resource use. Similarly, consumption efficiency rebounds may arise when repairable or upgradable products become more appealing or accessible, leading consumers to own more versions or variants than before. Although environmental burdens per unit decrease, total resource demand increases due to higher aggregate consumption.

Behavioural mechanisms also undermine circular objectives in product design. If consumers perceive circular products—such as those made from recycled materials—as inferior in terms of quality or performance, they may reject them in favour of conventional alternatives, sustaining resource-intensive production systems. Conversely, when circular options are accepted, they may activate other REs. For instance, a fashion brand marketing recycled clothing as a sustainable alternative may unintentionally boost sales: consumers feel reassured and justified in buying more, demonstrating how pro-environmental framing can fuel overconsumption.

Remanufacturing strategies can trigger similar unintended consequences. When remanufactured products are perceived—or function—as lower-quality substitutes, they may have shorter lifespans. Consumers then replace them more frequently, increasing total production and resource use. This imperfect substitution mechanism weakens the environmental gains expected from remanufacturing, especially in sectors where durability and performance are crucial.

Reuse strategies may also lead to REs. Lower prices for reused items can encourage consumers to purchase more—sometimes both reused and new products—triggering substitution and increasing overall consumption. Reuse initiatives can additionally activate single-action bias, where individuals consider one pro-environmental behaviour (e.g., choosing reused items) sufficient, reducing the likelihood of adopting other necessary circular practices.

Disassembly and recycling strategies are likewise vulnerable. Cost savings enabled by efficient disassembly can lower product prices, increasing demand and material throughput (composition mechanism). Recycling, while generally beneficial, can paradoxically raise energy use and processing demands. Intensive reuse of scrap materials may require additional processing steps, increasing the energy footprint, particularly when recycling is perceived as a standalone environmental solution (consumption efficiency mechanism).

Behavioural responses can further dilute the impact of circular initiatives. The introduction of recycling, for example, may trigger what is known as the contribution ethics mechanism, a perception that engaging in one sustainable action (e.g., recycling) reduces the motivation for others action. Companies or consumers may overemphasise the value of a single circular solution while neglecting broader, more impactful changes such as reducing consumption or redesigning business models.

Overall, REs in the product design process arise from systemic interactions between design choices, economic incentives, and both producer and consumer behaviour. While circular strategies reshape material and energy flows, their long-term success depends on careful consideration of these rebound dynamics. Anticipating behavioural responses, framing circularity appropriately, and integrating complementary measures are essential to ensure that product design strategies contribute meaningfully to sustainability and avoid reinforcing existing consumption patterns.

Table 12. Rebound mechanisms triggered by the CE strategies in procurement process

Circular strategies in Procurement	**Rebound mechanisms**	**Examples**
Close-loop supply chain and reverse logistics	Output	*A company implements a closed-loop supply chain strategy. The cost savings allow the company to expand production of refurbished goods, and as a result, the market sees an increase in the availability of these products, which may lead to higher overall consumption.*
	Supply adjustment/Sufficiency	*A company implements reverse logistics to reduce waste, but other producers in the market begin increasing their production of similar products, leading to a greater supply of new products that may still rely on virgin materials.*
	New market	*A company uses reverse logistics to create a secondary market for refurbished goods, shifting the economy and increasing demand for used products, which leads to higher production of secondary goods.*
	Economies of scale	*A company implements a closed-loop supply chain and reverse logistics to recover and reuse materials from returned products, improving overall resource efficiency. The reduced costs of reprocessing and reusing materials allow the company to lower the prices of the refurbished products. This price reduction leads to higher*

		demand for these products, ultimately increasing overall resource consumption and production volume.
	Behavioural income effect	*A company adopts reverse logistics by offering incentives for consumers to return old products, leading to cost savings that encourage purchasing new products, resulting in higher overall consumption.*
Industrial symbiosis and eco-industrial park	Frontier	*A group of industries optimizes resource exchanges to expand the production frontier, reducing waste, but, efficiency improvements in waste reuse lead to the creation of new products, such as eco-friendly materials, which increases overall resource demand*
	International	*A company in an eco-industrial park adopts advanced waste treatment technologies, improving efficiency. When the technology is transferred internationally to countries with looser regulations, it leads to increased output and resource consumption, rather than reducing environmental impact, due to the lack of sustainability incentives*
	New market	*An eco-industrial park adopts green technologies, creating a new market for eco-friendly products. As demand grows, more companies enter, leading to increased resource consumption.*
	Motivational crowding	*The government wants to reach 30% of recycling product, we have reached the 40% (we have done)*

The adoption of circular manufacturing strategies in the procurement process (Table 12)—particularly closed-loop supply chains, reverse logistics, and industrial symbiosis—can unintentionally trigger rebound mechanisms that undermine intended sustainability outcomes. Although these strategies aim to reduce resource extraction and waste generation, the interplay between market behaviour, production systems, and institutional responses can lead to effects that diverge significantly from initial environmental goals.

In closed-loop supply chains and reverse logistics, strategies designed to recapture value from used products often generate cost savings by increasing material-use efficiency. However, these savings may encourage producers to expand their operations, increasing the production and availability of refurbished goods. As refurbished products become more accessible and affordable, market demand may grow correspondingly. This rebound mechanism illustrates how interventions meant to reduce virgin material use can instead contribute to an overall expansion of supply, particularly when circular practices lower production costs.

Reverse logistics may also influence broader market behaviour. Competitors may respond to circular initiatives by scaling up production of similar—often less sustainable—products to remain competitive. This supply adjustment mechanism undermines sufficiency by increasing total production, which may still depend on virgin resources. As supply expands across the sector, the circular advantage becomes diluted by conventional market dynamics, especially in markets where price and availability outweigh sustainability in consumer decision-making.

Circular procurement can also activate new market mechanisms. The development of secondary markets for refurbished or remanufactured goods, facilitated by reverse logistics, is generally viewed as beneficial. However, their expansion can incentivise producers to manufacture goods specifically for these markets. Rather than replacing primary production, secondary production becomes an additional layer, increasing overall material throughput despite gains in circular efficiency.

As reverse logistics systems become more efficient, economies of scale may reduce the price of refurbished or recycled products. While lower prices improve accessibility, they can also stimulate demand, increasing total consumption. This highlights a core paradox of circular procurement: lowering environmental intensity per unit is insufficient if overall volumes increase due to affordability-driven demand.

Behavioural dynamics further complicate outcomes. Incentive schemes that reward consumers for returning old products—through discounts or vouchers—may reinforce a behavioural income effect, encouraging additional purchases rather than promoting sufficiency. Such mechanisms can unintentionally fuel higher consumption, contradicting the original sustainability intent.

Similar patterns arise in industrial symbiosis and eco-industrial parks, which aim to enhance efficiency through resource sharing, by-product exchange, and facility co-location. These strategies may trigger the frontier mechanism, enabling the creation of new product lines (e.g., eco-materials, bio-based outputs) that expand resource demand. While technologically innovative, such expansions can increase the complexity and intensity of procurement systems, raising overall resource use.

Environmental effects can also vary across institutional contexts. When eco-industrial innovations—such as advanced waste treatment or energy recovery—are transferred to regions with weaker regulations, they may stimulate increased production and resource extraction, amplifying global environmental impacts rather than reducing them. This highlights how international transfers of circular technologies can trigger unintended REs when regulatory alignment is lacking.

Industrial symbiosis may additionally activate the new market mechanism, drawing more firms into emerging green markets. As production scales and competition intensifies, industrial activity expands, potentially offsetting initial environmental gains if market growth is not carefully regulated.

Finally, motivational crowding may arise when externally imposed sustainability targets (e.g., recycling quotas) create a sense of completion once the goal is met. Companies achieving recycling rates above policy requirements may view their obligations as fulfilled, reducing intrinsic motivation to innovate or pursue further improvements. This complacency can limit long-term progress and undermine the transformative potential of circular procurement strategies.

These dynamics show that circular procurement is not immune to the economic, behavioural, and systemic forces that trigger rebound mechanisms. The examples underscore the need for a holistic approach that integrates regulatory frameworks, behavioural incentives, and market controls alongside technical optimisation. Only by anticipating and managing these feedback loops can circular procurement deliver its intended contribution to reducing environmental pressures and supporting a circular industrial transition.

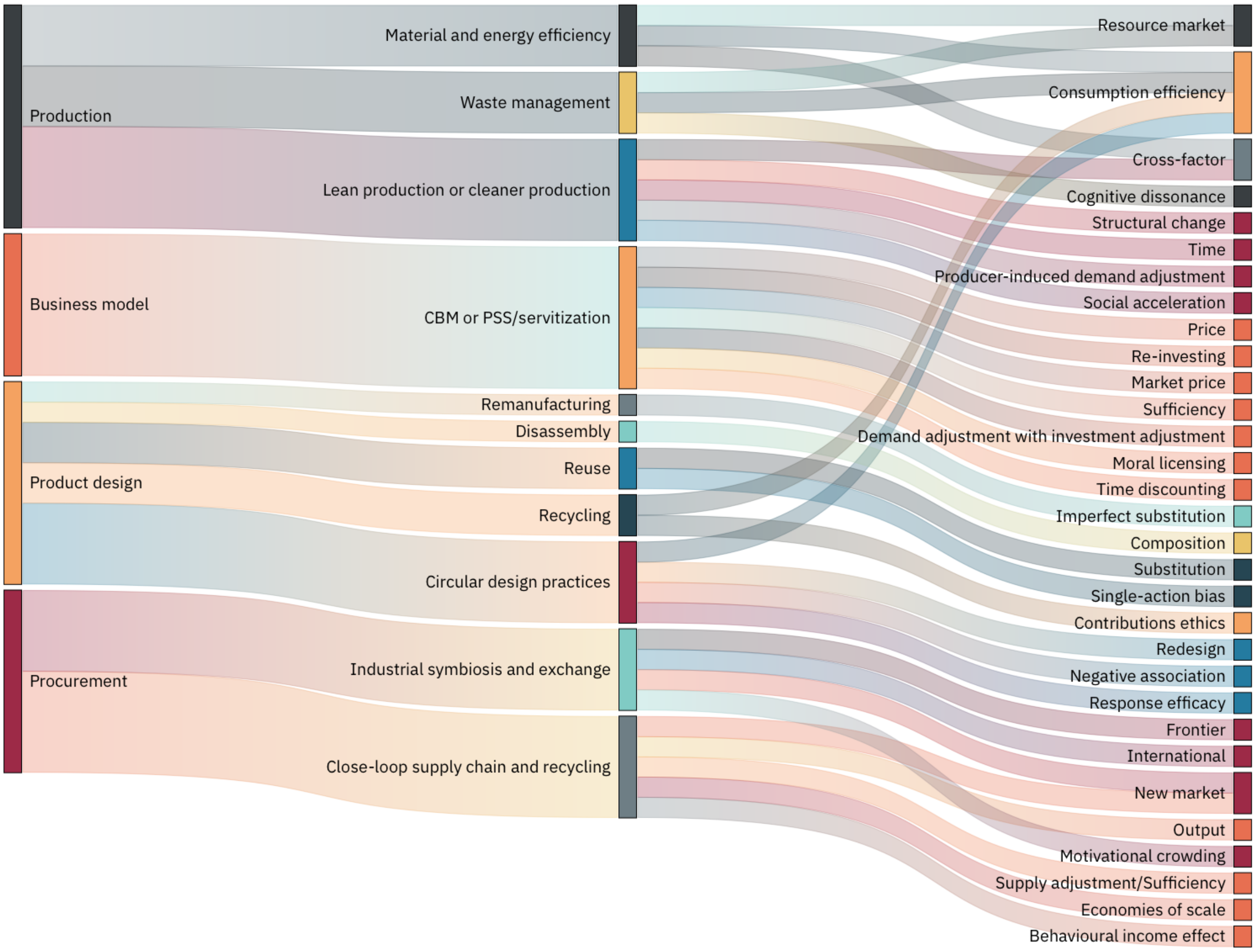


Figure 11. Visual synthesis of circular manufacturing strategies and associated rebound mechanisms.

Figure 11 synthesizes the associations discussed above by providing an integrated visual overview of how circular manufacturing strategies across the four business processes connect to rebound mechanisms. The left side of the diagram groups the circular strategies by business process, while the flows extending to the right map each strategy to the specific rebound mechanisms that may be triggered during implementation. The figure highlights how different strategies often converge toward similar rebound patterns, underscoring that REs do not stem from isolated interventions but from systemic feedback dynamics. Overall, this visual synthesis strengthens the understanding of the complexity, interdependencies, and cross-process nature of REs.

4.1.3 Analysis of the circular economy performance assessment methods

The third result emerging from the systematic literature review examines the methods used to assess CE performance, with the dual aim of understanding how CE performance has been evaluated in recent years and identifying which methods may support the detection of potential REs. A total of 76 papers published between 2018 and 2024 were identified, confirming a steadily growing interest in this research area.

Considering the nature of the contributions, three documents are conference papers, one is a book chapter, while the remaining ones are journal articles. The three scientific journals with the largest number of publications are:

Journal of Cleaner Production, *Sustainability (Switzerland),* with a total of 8 papers each, and *Resources, Conservation and Recycling* with a total of 7 articles.

Regarding the Country of affiliation of the first authors, the highest number of contributions come from European countries (49%). Particularly, the main number of papers comes from China, with 9 papers, followed by Italy and Spain, both with 8 papers, and the United Kingdom and Brazil, respectively, both with 5 documents.

Different types of research approaches were implemented. The majority of the papers adopted analytical research approaches (47%), followed by action research combined with application cases used to validate the study presented (32%), while the remaining contributions provided a theoretical assessment of the topic (21%). When application cases were conducted, different types of industry were involved, focusing on specific ones as construction (26%), automotive (13%), energy (11%), food (11%), and electronics (9%).

The 76 papers have been also analysed from a content perspective to understand which methods have been used to assess CE performance, categorised in Table 13. The performance assessment methods used in the selected papers include: Data Envelopment Analysis (DEA), a technique based on multi-input and multi-output linear programming to assess the relative efficiency of decision-making units; Design for X (DfX), approaches aimed at designing and developing circular products; life cycle assessment (LCA), an approach for evaluating the environmental impacts of a product throughout its lifecycle; multi-criteria decision making (MCDM), employing various methodologies to assess and compare multiple alternatives simultaneously; Emergy (Em) and Exergy (Ex) approaches, evaluating the use and quality of energy and materials within a system; Data Envelopment Analysis (DES), a technique used to analyse environmental and economic aspects to support effective production decisions; material flow analysis (MFA), a method for analysing material flows within a specific system; and other undefined methods.

The most adopted method has been the LCA, followed by the MCDM or fuzzy methods, but the category with the largest total was "Other" (i.e., those methodologies not previously grouped in the categories identified in this SLR). Papers, once categorised by method used, were also analysed based on the drivers presented in section 2, with a major focus on the variables involved (energy, material and pollution), the lifecycle stages addressed, and the TBL facets.

Table 13. Performance assessment methods used in the selected CE literature

	Methods used for CE performance assessment since 2018							
	DEA/I-O	**DfX/GL**	**LCA**	**MCDM/fuzzy methods**	**Em, EX**	**Simulation/DES**	**MFA/MCA/MFCA**	**Other**
Total	10	4	22	21	7	2	10	35

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting

Table 14 summarises the content of the studies using LCA. LCA emerged as the most widely employed method to assess different aspects of environmental performance related to CE implementation, ranging among different industries and focusing on several stages of the lifecycle. In fact, this category includes 22 documents, of which 17 are empirical analyses, while the remaining 5 present theoretical assessments. The empirical studies focus on evaluating circular practices related to environmental benefits in industries such as construction and wind turbines, as well as on assessing the potential of CE strategies. In these studies, LCA is often combined with other methodologies and serves as the base for the development of new tools. While the theoretical assessments provide insights into the use of LCA in relation to other methods or particular situations.

In particular, in relation to the empirical studies, multiple industries have been included in the papers selected. For instance, in the construction industry, LCA has been adopted not only to evaluate and compare different material alternatives (Alberto López Ruiz et al., 2022; Lei et al., 2022; Santos et al., 2022) but also to assess the environmental savings achieved by reuse practices and evaluate their efficiency (Antwi-Afari et al., 2021; Sanchez et al., 2019).

LCA has been used to assess different circular manufacturing strategies, focusing on the EoL stage. Indeed, papers covered different strategies, from the dismantling and recycling of wind turbine components to evaluate the level of circularity and carbon footprint (Diez-Cañamero and Mendoza, 2023; Kouloumpis et al., 2020), through the recovery of photovoltaic parts through thermal treatment (Lupu et al., 2020), and the recycling of plastic using hydrothermal treatment (Ozoemena and Coles, 2023), up to the environmental performance throughout the lifecycle of a textile product-service system (Bech et al., 2019).

In addition, LCA was used not only alone but also in combination with other methods. It has been employed to assess the environmental impact of CE practices and to analyse how these practices might be able to improve the overall systems' performance and reduce environmental impact in several EoL scenarios, involving various energy generation and power supply systems (Kourkoumpas et al., 2018; Stropnik et al., 2018). It has been also the basis for Em Analysis to evaluate both the environmental performance and the energy involved in a specific circular product system (de Souza Junior et al., 2020). At the same time, LCA and Life Cycle Cost (LCC), combined with MFA, have been used as part of an iterative process to assess the environmental and economic impacts of the role of materials in the implementation of circular strategies (Kulakovskaya et al., 2023).

Finally, not only different methods have been synergically applied together with LCA but also other types of tools have been developed based on LCA to assess the environmental impact of production systems from both an empirical and theoretical perspective. From the empirical one, an example is the Green Performance Map tool to identify waste and environmental losses in the production phase (Lindahl et al., 2022). Another one is the spiral infinite LCA, developed to overcome the limitations of LCA, and to improve recycling modelling approaches and identify standardisation practices for materials (Xie et al., 2024). Finally, a tool was developed and integrated to LCA to evaluate also the waste generated through the whole lifecycle and to assess the environmental footprint of dairy products (Egas et al., 2020). From a theoretical perspective, LCA has been often investigated, being object of several review studies, and sometimes exploited to propose new tools. In addition, looking at extant reviews in literature, LCA, together with other methods, has been largely investigated. In particular, some studies have investigated different methods to evaluate which method has been useful to perform CE performance assessment and promote the adoption of circularity to achieve the SDGs from an environmental perspective at the micro level

(Panchal et al., 2021). In addition, at the micro level, different methods (including LCA) have been analysed to assess the level of CE performance during the adoption in process and product to determine the most suitable (Roos Lindgreen et al., 2021). At the meso level, various methods have been compared and evaluated to assess the sustainability of companies from a technical, operational, and strategic perspective and to assess the impact of municipal solid waste and its management (Cobo et al., 2018; Marrucci et al., 2024). Finally, based on a SLR on CE performance assessment methods, a decision-making tool has been developed to help end-users choose the best approaches for CE (Aragonés and Torralvo, 2024).

Table 14 reveals that most papers (17) employ LCA in isolation or combined with other methods for empirical assessment, while the remaining five provide a theoretical evaluation, applying LCA alone or alongside other approaches. The table reports the variables analysed by these methods, mainly materials and energy in the empirical studies. The lifecycle stages involved during the use of LCA are mostly EoL, reflecting a focus on solutions before disposal. The TBL perspective considered is mainly environmental, particularly in empirical studies, which emphasize LCA's environmental aspect. Economic considerations appear in four empirical studies, while social aspects are addressed in one. Among theoretical studies, each dimension is considered a few times, environmental three times, economic, and social once.

Table 14. Content analysis of papers dealing with LCA: variables, lifecycle stages, and TBL dimensions involved.

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Kouloumpis et al., 2020)			X						X	X					X	X		
(Alberto López Ruiz et al., 2022)			X	X			X		X	X					X	X	X	
(de Souza Junior et al., 2020)			X		X				X	X		X	X	X	X	X		
(Kulakovskaya et al., 2023)			X				X			X	X				X	X	X	
(Ozoemena and Coles, 2023)			X						X	X	X				X	X		
(Lupu et al., 2020)			X						X		X				X	X		
(Bech et al., 2019)			X							X	X	X				X		
(Marrucci et al., 2024)			X						X	X		X	X	X	X	X		X
(Diez-Cañamero and Mendoza, 2023)			X							X					X	X		
(Santos et al., 2022)			X							X					X	X		
(Lei et al., 2022)			X					X	X	X					X	X	X	
(Sanchez et al., 2019)			X							X		X	X	X	X	X	X	
(Kourkoumpas et al., 2018)			X						X				X		X	X		

(Stropnik et al., 2018)			X						X	X					X	X		
(Antwi-Afari et al., 2021)	X		X		X		X			X		X	X	X	X	X		
(Xie et al., 2024)			X								X	X	X	X	X	X		
(Egas et al., 2020)			X								X				X	X		
Tot for empirical assessment	**1**	**0**	**17**	**1**	**2**	**0**	**3**	**1**	**9**	**13**	**6**	**6**	**6**	**5**	**16**	**17**	**4**	**1**
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Lindahl et al., 2022)			X					X	X			X	X	X	X	X		
(Roos Lindgreen et al., 2021)			X					X				X	X	X	X			
(Panchal et al., 2021)	X		X		X		X	X	X	X						X	X	X
(Cobo et al., 2018)			X	X			X		X	X	X	X	X	X	X	X		
Tot for theoretical assessment	**2**	**1**	**5**	**2**	**2**	**1**	**3**	**4**	**3**	**2**	**1**	**3**	**3**	**3**	**3**	**3**	**1**	**1**
TOTAL	**3**	**1**	**22**	**3**	**4**	**1**	**6**	**5**	**12**	**15**	**7**	**9**	**9**	**8**	**19**	**20**	**5**	**2**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 15 summarises the content of studies adopting multi-criteria approaches, twenty-one papers were identified. 17 of these conducted an empirical analysis, offering guidance on adopting this method to evaluate CE strategies at different lifecycle stages and various levels of analysis also combined with other methods, while the remaining 4 documents provided a theoretical assessment of this method.

From an empirical perspective, circular strategies such as reducing, reusing, recycling, recovering, remanufacturing, and redesigning were considered in a multi-criteria decision-making process to understand which are the best ones at different stages of the lifecycle of a given product (Asante et al., 2022) and to determine how to measure the development of environmental pillars in this context (Nikanorova and Stankevičienė, 2020). In addition to the evaluation of CE strategies, particularly recovery, a multi-criteria decision tool for product recovery was developed for EoL (Alamerew and Brissaud, 2019).

Multi-criteria and multi-objective methods were also used to evaluate the design phase of a product, combined with other methods such as DfX to determine which upcycled and reused materials should be used (Hapuwatte et al., 2022; Parece et al., 2022).

In addition to DfX, a multi-criteria approach was used in combination with other methods to assess different aspects of circularity. Specifically, a multi-criteria approach was used, combined with fuzzy logic and MFA. Together, the multicriteria and fuzzy logic approaches allowed the assessment of CE performance using indicators of different levels of analysis (micro, meso, and macro) for vehicle technology types (Ahmed et al., 2023) and using specific indicators to detect resource use, environmental treatment, and pollutant emissions to assess sustainability in China (Wang et al., 2021; Zhu et al., 2022). This type of analysis has been carried out to assess circularity in European countries (Banjerdpaiboon and Limleamthong, 2023; Candan and Cengiz Toklu, 2022), but also in other regions, using fuzzy logic (Garcia-Bernabeu et al., 2020), combined with MFA (Van Bueren et al., 2021). To evaluate and compare the CE strategies adopted in different countries, a type of multi-criteria approach called the Analytic Hierarchy Process (AHP) is used to rank alternatives (Xijie et al., 2023). AHP has been used to assess CE in automobile maintenance garages and to assess the remanufacturability of car systems during the design phase (James et al., 2023, 2021).

Additionally, MCDM have been used to evaluate and compare various aspects of the value chain of products and processes based on circularity (Ahmed et al., 2022b), starting with improving the circularity performance of the supply chain (Mishra et al., 2023).

At the micro level, multi-criteria were combined with LCA and MFA to assess the circular alternative for waste such as construction and demolition waste and municipal solid waste (Alberto López Ruiz et al., 2022; Cobo et al., 2018).

From a theoretical perspective, the multi-criteria approach was mostly used to assess the different aspects or criteria of circularity simultaneously, providing qualitative and quantitative data useful for decision making (Aragonés and Torralvo, 2024). For example, eight sustainability indicators were considered in a multi-criteria approach to evaluate the progress of the different CE principles and SDGs at the nano and macro levels (de Oliveira and Oliveira, 2023).

As shown in Table 15, the multi-criteria method and fuzzy logic are predominantly found in the empirical assessment category (17 papers), where they are typically applied individually rather than in combination with other methods. In contrast, the theoretical studies (4 papers) primarily analyse these methods in relation to other approaches. A content analysis of the empirical studies reveals that these methods are mainly applied from environmental and economic perspectives, with only four papers addressing the social perspective. These methods evaluate all three variables—energy, materials, and pollution. Furthermore, most of the CE assessments focus on the BoL, particularly the design and development phase of new products, their evaluation, and the EoL phase. In contrast, the theoretical assessments evaluate the multi-criteria and fuzzy logic methods consistently across all the perspectives mentioned.

Table 15. Content analysis of papers dealing with multicriteria: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Wang et al., 2021)	X			X							X				X	X	X	
(Hapuwatte et al., 2022)				X				X		X		X				X	X	X
(Alberto López Ruiz et al., 2022)			X	X			X		X	X					X	X	X	
(Asante et al., 2022)				X					X	X		X	X	X	X			
(Mishra et al., 2023)				X					X		X	X	X	X	X	X		
(Nikanorova and Stankevičienė, 2020)				X					X		X					X	X	
(Alamerew and Brissaud, 2019)				X						X					X	X	X	X
(Banjerdpaiboon and Limleamthong, 2023)	X			X				X		X	X					X		
(Zhu et al., 2022)				X					X		X					X		
(Garcia-Bernabeu et al., 2020)				X					X	X		X	X	X	X	X	X	
(Parece et al., 2022)		X		X						X		X	X	X	X	X		
(Ahmed et al., 2023)				X					X		X	X	X	X	X	X	X	X

(Ahmed et al., 2022b)				X					X			X	X	X	X	X	X	
(Candan and Cengiz Toklu, 2022)				X						X	X					X	X	
(James et al., 2023)				X							X					X		
(James et al., 2021)				X						X					X			
(Xijie et al., 2023)				X											X	X	X	X
Tot for empirical assessment	**2**	**1**	**1**	**17**	**0**	**0**	**1**	**2**	**8**	**9**	**8**	**7**	**6**	**6**	**11**	**15**	**10**	**4**
(de Oliveira and Oliveira, 2023)				X						X	X				X	X	X	X
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Van Bueren et al., 2021)				X	X		X		X	X						X		
(Cobo et al., 2018)			X	X			X		X	X	X	X	X	X	X	X		
Tot for theoretical assessment	**1**	**1**	**2**	**4**	**2**	**1**	**3**	**1**	**2**	**3**	**2**	**1**	**1**	**1**	**2**	**3**	**1**	**1**
TOTAL	**3**	**2**	**3**	**21**	**2**	**1**	**4**	**3**	**10**	**12**	**10**	**8**	**7**	**7**	**13**	**18**	**11**	**5**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 16 summarises the studies using DfX. DfX was detected only in a few studies, mostly presenting an empirical analysis. This approach focused on concurrent product and process design specifications, working in the development phase on constraints and requirements to develop sustainable, competitive, and profitable products (Aragonés and Torralvo, 2024). Specific DfX approaches were considered in the construction industry. Design for Disassembly was adopted to evaluate the disassembly potential for structural elements (Khadim et al., 2023) to be recycled and recovered during demolition and reused in new infrastructure (Lei et al., 2023). Design for Adaptability was employed to assess the adaptability of the building to live in and the obsolescence level (Parece et al., 2022).

Table 16 provides an overview of the papers examining the DfX approach, categorised into empirical and theoretical studies. In empirical studies, when DfX is combined with other methods and MCDM, the primary focus is on material variables. In contrast, studies applying DfX alone also consider factors such as energy and pollution. This approach primarily analyses the environmental perspective at EoL stage, emphasising environmental considerations in the adoption of circular solutions before disposal. Theoretical studies, on the other hand, offer a broad overview of DfX in conjunction with various other methods without delving into specific aspects.

Table 17 summarises the papers employing DEA and input-output (I-O) approaches. I-O analysis, and in particular the DEA methodology, have been identified in several papers; 7 of them conducted an empirical evaluation at different levels of analysis in combination with other methods, and the remaining provided a theoretical study. I-O analysis was used to provide a way to analyse the relationships between resources used and products or services generated in the system to assess efficiency and productivity. In particular, system productivity was assessed by considering interdependencies between processes or economic sectors, while efficiency was compared among different decision-making units (Aragonés and Torralvo, 2024).

The DEA methodology was applied to evaluate the resource-use efficiency of multi-input and multi-output decision-making units, mainly from a macro perspective. It was used to measure the CE performance and growth rate of several cities in China to evaluate the efficiency of circular strategies (Shang et al., 2022), to measure the industrial CE performance of a specific industry in China, considering several I-O variables such as industrial production (Ding et al., 2020a), and to evaluate a large data set to determine the performance and efficiencies of the urban CE (Wang et al., 2021).

The DEA methodology was used in most times combined with other approaches. It was integrated as part of a two-stage cooperative game to evaluate economic production and environmental treatment to assess the level of CE performance of the ocean in China's coastal regions (Ding et al., 2020b). It was combined with ten environmental and circular performance indicators to assess the performance of waste management in European countries (Giannakitsidou et al., 2020), providing a ranking of European Union countries that considered waste generation and the results of introducing circular strategies (e.g., recycling) (Banjerdpaiboon and Limleamthong, 2023). It has also contributed to the analysis of data to assess the CE performance and improve it to achieve the SDGs (Panchal et al., 2021). This kind of method has also been used in combination with other methods (e.g., LCA and MFA) to better assess environmental performance in the construction and food sectors (Antwi-Afari et al., 2021; Jacob et al., 2021).

From Table 17, it emerged that the DEA and I-O methods are detected in empirical assessment (7 documents) and theoretical assessment (3 documents). In the empirical studies, these methods are largely adopted in isolation, and only material and pollution data are evaluated from an environmental and economic perspective, without particular focus on the lifecycle stages. In the theoretical assessment, these methods are studied with other approaches, considering only the TBL aspects.

Table 16. Content analysis of papers dealing with DfX: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Khadim et al., 2023)		X						X		X					X	X		
(Lei et al., 2023)		X							X	X	X				X	X		
(Parece et al., 2022)		X		X						X		X	X	X	X	X		
Tot for empirical assessment	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**3**	**1**	**1**	**1**	**1**	**3**	**3**	**0**	**0**
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
Tot for theoretical assessment	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
TOTAL	**1**	**4**	**1**	**2**	**1**	**1**	**1**	**2**	**1**	**3**	**1**	**1**	**1**	**1**	**3**	**3**	**0**	**0**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 17. Content analysis of papers dealing with DEA: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Wang et al., 2021)	X			X							X				X	X	X	

(Shang et al., 2022)	X															X		
(Giannakitsidou et al., 2020)	X										X					X	X	X
(Banjerdpaiboon and Limleamthong, 2023)	X			X				X		X	X					X		
(Ding et al., 2020a)	X										X					X	X	
(Ding et al., 2020b)	X										X					X	X	
(Antwi-Afari et al., 2021)	X		X		X		X			X		X	X	X	X	X		
Tot for empirical assessment	**7**	**0**	**1**	**2**	**1**	**0**	**1**	**1**	**0**	**2**	**5**	**1**	**1**	**1**	**2**	**7**	**4**	**1**
(Jacob et al., 2021)	X						X	X		X						X	X	
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Panchal et al., 2021)	X		X		X		X	X	X	X						X	X	X
Tot for theoretical assessment	**3**	**1**	**2**	**1**	**2**	**1**	**3**	**3**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**2**	**2**	**1**
TOTAL	**10**	**1**	**3**	**3**	**3**	**1**	**4**	**4**	**1**	**4**	**5**	**1**	**1**	**1**	**2**	**9**	**6**	**2**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 18 summarises the content of MFA-based studies. MFA has been identified in several papers. MFA aims to assess the sustainability and efficiency of material use by evaluating the material flow from resource consumption to waste generation, resource use efficiency, and the environmental impact generated (Aragonés and Torralvo, 2024). To this purpose, the MFA has been used to assess the circular lifecycle aspects of certain types of materials, such as expanded polystyrene (Kulakovskaya et al., 2023).

The evaluation of the MFA method addressed resource use and waste management from both an environmental and economic perspective, using material flow cost accounting (MFCA), which focused on the financial potential caused by material and energy practices (Jacob et al., 2021; Rocca et al., 2021). This resource assessment was used to calculate resource productivity and to determine the rate and amount of waste disposal, aiming to optimise resource use at the city level (Gao et al., 2021). Simultaneously, the analysis assessed the efficiency of municipal solid waste management (Cobo et al., 2018) and waste generated (Alberto López Ruiz et al., 2022) by construction and demolition activities, supporting circular performance in the construction sector (Antwi-Afari et al., 2021).

The MFA and MFCA have been applied not only to assess circular performance at the urban level but also at the macro level to evaluate the use and management of materials, energy, and waste produced by entire regions and nations (Panchal et al., 2021; Van Bueren et al., 2021).

Table 18 reports the papers where MFA is detected, with an equal distribution between empirical and theoretical studies. In the empirical studies, MFA is often applied in combination with other methods, mostly with LCA. This combined use of methods is particularly valuable as it enables a comprehensive evaluation of CE performance. This combination provides a complete evaluation of both environmental and economic impacts, particularly at the EoL stage. LCA evaluates the environmental perspective, while MFA offers insights into material flows, identifying inefficiencies and potential for recovery. The incorporation of these methods captures the environmental impacts of material use and also the economic implications of material use efficiency. In the theoretical assessment, MFA is studied considering the environmental and economic impact of materials without reference to a particular lifecycle stage.

Table 19 summarises the studies using Em and Ex analyses. Em and Ex analysis have been identified in a few papers and have always been combined with other methods, especially LCA and MFA, to assess environmental impacts and material flows. These approaches evaluated the use, efficiency, and quality of energy and materials in the system to assess environmental impact, energy efficiency, and sustainability and identify opportunities for improvement in energy efficiency and sustainability (Aragonés and Torralvo, 2024). The Ex analysis, in synergy with the LCA, provided an environmental and energy analysis of recycled expanded polystyrene in the logistics and transport sectors (de Souza Junior et al., 2020). Ex capabilities were used with LCA, MFA, and I-O methods to assess the energy requirements of different building materials (Antwi-Afari et al., 2021). Ex analysis has been used with a simulation process to assess material and energy degradation (Bartie et al., 2021). Em analysis was used to assess environmental impact by measuring the amount of waste and recycled or reused materials (Panchal et al., 2021). Em analysis combined with MCMD and MFA was used to identify system boundaries during the implementation of circular strategies (Van Bueren et al., 2021).

Only one study used Em analysis without other methods. It was used to evaluate economic, social, and environmental performance to assess the sustainability of the supply chain (Alkhuzaim et al., 2021).

Table 19 shows the combination of Em and Ex analysis with other methods in empirical and theoretical studies. In the empirical assessment, the two most studied variables are energy and materials only from an environmental perspective, considering all the different lifecycle stages. In the theoretical assessment, these methods are studied considering energy and materials as variables from all the TBL perspectives, but neglecting lifecycle phases.

DES was identified only twice, as shown in Table 20, once in empirical and once in theoretical assessment. The papers adopted simulation combined with other methods to evaluate material and energy aspects in the whole lifecycle from an environmental perspective.

DES was used to analyse and optimise environmental and economic aspects through simulations using conditions and parameters to analyse system performance under different conditions represented by a “what if” scenario to support process optimisation (Aragonés and Torralvo, 2024). Based on this definition, a simulation approach has been used to evaluate system response to change due to different transformations during the production and recycling processes (Bartie et al., 2021).

Table 18 Content analysis of papers dealing with MFA: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Alberto López Ruiz et al., 2022)			X	X			X		X	X					X	X	X	
(Kulakovskaya et al., 2023)			X				X			X	X				X	X	X	
(Gao et al., 2021)							X	X		X	X					X		X
(Rocca et al., 2021)							X			X		X	X	X	X	X	X	
(Antwi-Afari et al., 2021)	X		X		X		X			X		X	X	X	X	X		
Tot for empirical assessment	**1**	**0**	**3**	**1**	**1**	**0**	**5**	**1**	**1**	**5**	**2**	**2**	**2**	**2**	**4**	**5**	**3**	**1**
(Jacob et al., 2021)	X						X	X		X						X	X	
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Panchal et al., 2021)	X		X		X		X	X	X	X						X	X	X
(Van Bueren et al., 2021)				X	X		X		X	X						X		
(Cobo et al., 2018)			X	X			X		X	X	X	X	X	X	X	X		
Tot for theoretical assessment	**3**	**1**	**3**	**3**	**3**	**1**	**5**	**3**	**3**	**4**	**1**	**1**	**1**	**1**	**1**	**4**	**2**	**1**
TOTAL	**4**	**1**	**6**	**4**	**4**	**1**	**10**	**4**	**4**	**9**	**3**	**3**	**3**	**3**	**5**	**9**	**5**	**2**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 19 Content analysis of papers dealing with Em and Ex analysis: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Bartie et al., 2021)					X	X			X	X		X	X	X	X	X		
(de Souza Junior et al., 2020)			X		X				X	X		X	X	X	X	X		
(Antwi-Afari et al., 2021)	X		X		X		X			X		X	X	X	X	X		
Tot for empirical assessment	**1**	**0**	**2**	**0**	**3**	**1**	**1**	**0**	**2**	**3**	**0**	**3**	**3**	**3**	**3**	**3**	**0**	**0**
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Alkhuzaim et al., 2021)					X				X	X						X	X	X
(Panchal et al., 2021)	X		X		X		X	X	X	X						X	X	X
(Van Bueren et al., 2021)				X	X		X		X	X						X		
Tot for theoretical assessment	**2**	**1**	**2**	**2**	**4**	**1**	**3**	**2**	**3**	**3**	**0**	**0**	**0**	**0**	**0**	**3**	**2**	**2**
TOTAL	**3**	**1**	**4**	**2**	**7**	**2**	**4**	**2**	**5**	**6**	**0**	**3**	**3**	**3**	**3**	**6**	**2**	**2**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 20. Content analysis of papers dealing with DES: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage: BoL		Lifecycle Stage		TBL		
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Bartie et al., 2021)					X	X			X	X		X	X	X	X	X		
Tot for empirical assessment	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**0**	**0**
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
Tot for theoretical assessment	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
TOTAL	**1**	**1**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**		**1**	**1**	**1**	**1**	**1**	**0**	**0**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

Table 21 summarises the studies using assessment approaches not included in the categories above.
The largest number of articles presented other methods for evaluating circular performance, as shown in Table 21. Some studies offered a new method for evaluating circular strategies, while others proposed other methods in addition to the known ones, providing an empirical analysis 23 times and 13 times through a theoretical study.
In the construction sector, several new methods were developed and proposed. The potential adoption of circular strategies in buildings has been assessed through the Whole Building Circular Indicator, which studies the materials, elements, and systems that form a building (Khadim et al., 2023) to measure recycling rate and energy recovery rate (Lei et al., 2022). Also, a mathematical tool was developed to evaluate the reusability of materials based on the building's age (Akanbi et al., 2019). An additional building assessment tool to promote sustainability, developed on the basis of the SDGs, was the Sustainability Assessment Tool (SBTool^{PT}), which aims to certify whether sustainability criteria, such as environmental quality, energy efficiency, waste management, social aspects, economic development, and innovation, have been achieved (Cervantes Puma and Bragança, 2024). Construction project-level indicators were identified in literature and then divided into four categories: input-related, output-related, process-related, and people-related. These indicators were adopted to assess different aspects of circularity during the construction of a new building (Jayakodi et al., 2024).
In the automotive industry, CE strategies (e.g., reuse and recycling) have been evaluated through different KPIs, which assess greenhouse gas impact, waste generation, and CO_2 emissions (Pidikiti et al., 2023). In addition, some of these indicators have been grouped into a framework called MICRON (*MIcro CirculaR ecOnomy iNdex*) to assess the durability of automotive materials, the generated waste, and specific CO_2 emissions (Baratsas et al., 2022).
To assess the level of CE of agri-food companies, a tool was developed based on the evaluation of several variables (such as economic cycle, consumption and use, regeneration, and sustainability) to which were given special weight (Diéguez-Santana et al., 2021). Furthermore, in the food industry, additional methods, such as Material Circular Indicator and Material Reutilization Score, combined with LCA, were employed to measure the treatment of food waste (e.g., anaerobic digestion and bioconversion) and to calculate the reusability score and the raw material score (Roos Lindgreen et al., 2021), thereby assessing their environmental impact. Moreover, two approaches were adopted to assess the costs associated with the food industry: LCC and cost-benefit analysis to better estimate the economic potential of CE implementation (Jacob et al., 2021). When combined with LCA, these approaches provide a more comprehensive assessment, integrating both economic and environmental dimensions of food waste treatment and its circular potential.
In the WEEE industry, a framework of environmental, social, and economic indicators has been developed to measure and monitor the circularity of products (Pollard et al., 2022). In particular, a design tool has been developed to assess the sustainability performance of products and to maximise the benefits of production (Hapuwatte et al., 2022) by assessing product longevity, recyclability, and recovery of secondary raw materials (Rossi et al., 2020). Maturity-level assessments based on the SDGs have also been developed to advance sustainable e-waste initiatives (Fatimah et al., 2024; Panchal et al., 2021).
Beyond the industrial sector, several approaches have been used to assess the environmental performance of small and medium-sized enterprises. The Green Performance Map was developed to measure environmental waste and

losses in the production stage (Lindahl et al., 2022). A number of companies were analysed through surveys and permutation tests to assess the adoption of environmentally friendly practices that can reduce raw materials, waste, and investments (Bonnini et al., 2024). In addition, a series of indicators were identified that assess social responsibility and environmental and governmental aspects (Blinova et al., 2023) and categorised into a framework indicating the economic, environmental, and social aspects considered (Negri et al., 2021).
Circularity in companies was also assessed using a tool that scores the different categories of circular performance to understand the level of sustainability awareness and actions taken (Sacco et al., 2021). CE performance indicators in companies evaluated production and consumption, waste management, secondary raw materials, and competitiveness and innovation. This set of indicators was used to assess circular actions at the micro level (Rincón-Moreno et al., 2021). Based on the indicators and indexes found in the literature, several tools have been developed. In particular, a decision support tool for stakeholders to select the best CE approach (Aragonés and Torralvo, 2024), also assessed through SWOT analysis (Papamichael et al., 2023), as well as a map of the main characteristics of CE performance evaluation methods, taking into account the evolution over time (de Figueiredo Sarmento et al., 2024; Lopes et al., 2024).

At the supply chain level, circular performance was assessed through a set of indicators grouped into five classes: monetary, energy and environment, material, temporal, and efficiency (Lee et al., 2024). In particular, these indicators enabled the evaluation of resource flows and availability, water and energy use, and overall system effectiveness in circular supply chains. Additionally, circular performance assessment considered aspects such as resource recovery, waste minimisation, and closed-loop logistics to enhance sustainability across supply chain operations (Vegter et al., 2023b). The adoption of indicators and methods to assess circular supply chains were able to identify the disruptions that can occur in a supply chain. The use of KPIs was aided by the Industry 4.0 technologies (Fernando et al., 2023; Nandi et al., 2023) in contributing to achieving SDGs (Ahmed et al., 2022a). Industry 4.0 has a crucial role in improving CE practices, facilitating real-time monitoring, predictive maintenance, and enhanced traceability of materials, thereby improving resource efficiency and reducing waste (Cattelan Nobre et al., 2023). In addition, a decision support system was adopted to evaluate CE practices in the forest-wood supply chain (Sacchelli et al., 2022). The integration of digital technologies within such systems further strengthens circular supply chain management, enabling more accurate assessments and promoting data-driven sustainability strategies (Taddei et al., 2022).
At the city level, the CE performance was assessed from an ecological perspective using various indicators that took into account resource productivity, recycling rates, and waste disposal volumes (Gao et al., 2021).
At the macro level, CE targets and indicators have been identified in specific countries to assess progress towards sustainability, both from a waste management point of view by measuring municipal waste generation and from a social point of view by examining the level of education using various tools (Droege et al., 2021; Valls-Val et al., 2023). Municipal waste generation has been assessed in European countries to rank them (Banjerdpaiboon and Limleamthong, 2023). All these criteria have been used to provide a regional-level picture of the implementation of circular strategies (van Bueren et al., 2022).

Table 19 presents the combination of other methods with those previously proposed in various documents, with 22 from empirical studies and 13 from theoretical studies. The most commonly investigated variable is materials, examined through the adoption of other methods, followed by energy, which is primarily analysed at the EoL stage from an environmental perspective, though also from economic and social perspectives. In the theoretical assessments, the focus is predominantly on energy and material variables, without reference to specific lifecycle stages, and is mainly considered from an environmental perspective, alongside economic and social aspects.

Table 21 Content analysis of papers dealing with other methods: variables, lifecycle stages, and TBL dimensions involved

Authors	Method								Variables			Lifecycle Stage				TBL		
												BoL						
	DEA/ I-O	DfX/ GL	LCA/ LCI/ LCIA	MCDM/fuzzy methods	Em, Ex	Simulation/DES	MFA/ MCA/ MFCA	Other	E	M	P	Product D&D and strategic evaluation	Manufacturing	MoL	EoL	Env	Econ	Soc
(Khadim et al., 2023)		X						X		X					X	X		
(Bonnini et al., 2024)								X		X						X	X	X
(Cervantes Puma and Bragança, 2024)								X	X	X						X	X	X
(Lee et al., 2024)								X		X					X			
(Akanbi et al., 2019)								X		X					X			
(Fernando et al., 2023)								X		X	X					X		
(Hapuwatte et al., 2022)				X				X		X		X				X	X	X
(Gao et al., 2021)							X	X		X	X					X		X
(Nandi et al., 2023)								X		X						X	X	X
(Droege et al., 2021)								X								X	X	
(Rossi et al., 2020)								X		X		X	X	X	X	X	X	X
(Sacco et al., 2021)								X		X						X		X
(Banjerdpaiboon and	X			X				X		X	X					X		

Limleamthong, 2023)																		
(Pidikiti et al., 2023)								X	X			X	X	X	X	X	X	X
(Diéguez-Santana et al., 2021)								X			X					X		
(Rincón-Moreno et al., 2021)								X	X	X	X	X	X	X	X	X	X	
(Valls-Val et al., 2023)								X		X								X
(Baratsas et al., 2022)								X	X		X	X	X	X	X	X	X	
(Lei et al., 2022)			X					X	X	X						X	X	X
(Sacchelli et al., 2022)								X	X			X	X	X	X	X		
(Fatimah et al., 2024)								X	X	X		X			X	X	X	X
(Van Bueren et al., 2021)								X			X					X	X	X
(Pollard et al., 2022)								X	X	X		X	X	X	X	X	X	X
Tot for empirical assessment	**1**	**1**	**1**	**2**	**0**	**0**	**1**	**22**	**7**	**17**	**6**	**7**	**5**	**5**	**10**	**19**	**13**	**11**
(Jacob et al., 2021)	X						X	X		X						X		
(Lopes et al., 2024)								X										
(de Figueiredo Sarmento et al., 2024)								X										

(Papamichael et al., 2023)								X										
(Blinova et al., 2023)								X	X							X	X	X
(Aragonés and Torralvo, 2024)	X	X	X	X	X	X	X	X										
(Lindahl et al., 2022)			X					X	X			X	X	X	X	X		
(Roos Lindgreen et al., 2021)			X					X				X	X	X	X			
(Panchal et al., 2021)	X		X		X		X	X	X	X						X	X	X
(Ahmed et al., 2022a)								X	X	X		X	X	X	X	X	X	X
(Negri et al., 2021)								X	X	X		X	X	X	X	X	X	X
(Jayakodi et al., 2024)								X		X		X	X	X	X	X		
(van Bueren et al., 2022)								X			X					X	X	X
Tot for theoretical assessment	**3**	**1**	**4**	**1**	**2**	**1**	**3**	**13**	**5**	**5**	**1**	**5**	**5**	**5**	**5**	**8**	**5**	**5**
TOTAL	**4**	**2**	**5**	**3**	**2**	**1**	**4**	**35**	**13**	**22**	**7**	**12**	**10**	**10**	**15**	**27**	**18**	**16**

DEA= Data Envelopment Analysis; I-O= Input-Output; DfX= Design for X; GL= Guidelines; LCA=Life Cycle Assessment; LCI= Life Cycle Inventory; LCIA= Life Cycle Impact Assessment; MCDM= Multi-Criteria Decision-Methods; Em= Emergy approach; Ex= Exergy approach; DES= Discrete Event Simulation; MFA= Material Flow Analysis; MCA= Material Cost Analysis; MFCA= Material Flow Cost Accounting; E = energy; M = material; P = pollution; BoL = Beginning of Life; MoL = Middle of Life; EoL = End of Life; Env = Environmental; Econ = Economical; Soc = Social

4.2 Results from Stage 2: Descriptive Study I

The section presents the results obtained in the second stage of the DRM, *Descriptive Study I.*

4.2.1 Mapping the relations between the dimensions of circular economy and rebound effects

From in-depth systematic literature review regarding the five CE-RE dimension, 68 contributions were selected and analysed for the year of publication, first author nationality, journal of publication, the industry concerned, and research types. The selected documents span the years 2013 to 2023, showing a significant rise in interest during the last few years (2021-2023) in the CE topic across all the five fields. In the light of author nationalities, the highest numbers of contributions came from European countries (57%), in particular, Italy with 13 papers, the United Kingdom (8), Sweden (7), Germany, and Denmark (5), followed by Brazil with 12% of documents. Nearly all contributions were journal articles (96%), with only 4% published in international conference proceedings. The journals with the highest number of contributions to the research field are the *Journal of Cleaner Production, Sustainability (Switzerland),* and *Sustainable Production and Consumption*. Most of the selected contributions provided theoretical assessment (61 on 68), while the remaining ones (7 on 68) combined theoretical research with applied case studies. In 45 documents, multiple industries were included in the research conducted. The main industries involved are textile (42%), chemical (16%), plastic (16%), automotive (11%), and others.

The selected contributions provide a foundation for a more detailed assessment of the five dimensions (i.e., Business models, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects) and for mapping the links among their related factors. The papers were classified according to these dimensions, and the collected data are reported in Tables 22 – 26, presenting each reference (with an identifying number for use in the conceptual maps in Figures 12 and), the study objective, and its main output.
The Business models dimension (Table 22) focuses on strategies to create, deliver, and capture value in a company involving the CE paradigm. Therefore, the adoption of business models was increased by four circular strategies: recycling, extending, intensifying, and dematerialising (Geissdoerfer et al., 2020). To foster these mechanisms and align the business models with CE principles (Sehnem et al., 2022), innovation turned out to be a positive aspect, being able to convert waste into resources for production (Kuzma et al., 2021). In addition, different studies were carried out to evaluate how the traditional business models changed within closed material loops (e.g., circular business model (Bocken et al., 2016)). In fact, a variation of the business model Canvas has been proposed (Salvador et al., 2021): its nine blocks offer strategies to implement and manage the reduction or elimination of resource leakage and include a take-back system. At this purpose, the adoption of circular business models can depend on recall, reuse, refurbishment (Mhatre et al., 2021), and reverse logistics (Abideen et al., 2021) dynamics. On these four practices, five types of business model were developed: circular inputs, resource recovery, life-cycle extension (that promoted extending product life like next life sales (Upadhyay et al., 2019)), PSS, and collaboration platforms (Försterling et al., 2023). This last type of business model is based on increasing the use of a product or

service through sharing dynamics (De Bruyne and Verleye, 2023). PSS represents a business model archetype widespread in different sectors (Rosa et al., 2019a; Salvador et al., 2020), such as the WEEE sector (Rosa et al., 2019b).

These diverse types of circular business model can also be influenced by consumers' perceptions (Gomes et al., 2022). The CE business model is implemented at three levels: micro (single firm or customer level), meso (inter-firm level), and macro (city, province, region, and national level) (Merli et al., 2018). CE is involved in the supply chain through the vertical integration of micro level actors and key activities (Bressanelli et al., 2019; Vegter et al., 2020). At the inter-firm level, industrial symbiosis or eco-industrial parks are discussed in urban cities (Chauhan et al., 2022; Munaro et al., 2020). At the regional level, different barriers and opportunities are recognised towards the implementation of CE in four countries (Salvador et al., 2022).

Circular business model is evaluated through environmental performance (van Loon et al., 2021b) and financial performance (e.g., costs and revenues) (Kanzari et al., 2022). Digital technologies improved the circular business model; in fact, they offer and support the adoption of circular strategies (Eisenreich et al., 2022) in the value chain (S. Ding et al., 2023), including tracking, monitoring, and control (Cioffi et al., 2020).

Table 22. Business model dimension

References	n.	Objective	Output
(S. Ding et al., 2023)	[1]	Recognise the benefits of internet of things capabilities and their potential for reducing carbon emissions in circular business model.	Relationship framework for internet of things enabled 6R and circular business model.
(Försterling et al., 2023)	[2]	Analyse new sustainable business models.	Frameworks of circular business model Drivers and Barriers.
(De Bruyne and Verleye, 2023)	[3]	Determine the parameters that sharing business models may vary along with and analyse their influence on consumer involvement.	Sets of sharing-based business models
(Eisenreich et al., 2022)	[4]	Examine the effects of introducing circular solutions in a company's value chain processes.	A new circular value chain framework to connect operational and processual
(Sehnem et al., 2022)	[5]	Investigate the current intersection of the concepts of CE and innovation	A conceptual framework of 6 propositions
(Gomes et al., 2022)	[6]	Determine consumer attitudes and behaviour in CE literature along with the elements that impact, hinder, and enhance customer engagement.	Theoretical framework for circular consumption
(Chauhan et al., 2022)	[7]	Examine how CE and digitalization technologies interact.	Framework to include digitalization in the CE transition: a viable system model
(Salvador et al., 2022)	[8]	Identify the drivers, opportunities, challenges, and barriers for businesses in a circular bioeconomy, both from theoretical and practical perspectives.	Set of barriers, challenges, and drivers for circular bioeconomy
(Kanzari et al., 2022)	[9]	Examine the scope, setting, and substance of discussions regarding financial performance related to the transition to circular business model	3-step analysis frameworks for circular business model performance
(Salvador et al., 2021)	[10]	Explain key components for adopting and managing circular bioeconomy business models, as well as the challenges surrounding the theme	Framework to develop and manage a business model for circular bioeconomy.
(Kuzma et al., 2021)	[11]	Analyse the relationship between CE and entrepreneurship	Map an organisation on the topics that CE and entrepreneurship examine.
(Mhatre et al., 2021)	[12]	Identify the business models used by businesses and the CE techniques used in the various economic sectors.	Set of CE strategies implemented in the EU
(Abideen et al., 2021)	[13]	Research the use of technology in the circular supply chain	A roadmap for the operating model of the circular supply chain as it is influenced by digital technologies

(van Loon et al., 2021a)	[14]	A comparison of the environmental effects of linear and circular business models	Map of factors influencing the effects of circular products and circular business model on the environment
(Salvador et al., 2020)	[15]	Identify research on circular business models worldwide, in addition to the key factors influencing their implementation, as also as highlight study topics and publications that publish it.	Set of circularity aspects in business model
(Munaro et al., 2020)	[16]	Examine how the CE is covered and studied in the built environment.	Framework of CE in the construction industry to support political actions
(Cioffi et al., 2020)	[17]	Examine how the advancement of digital technologies could contribute to CE models.	Set of digital manufacturing actions
(Vegter et al., 2020)	[18]	In a circular business model, describe the notions of operations and performance goals of a supply chain.	Set of key activities
(Bressanelli et al., 2019)	[19]	Classify the CE problems for supply chain redesign and suggest ways to overcome them.	Set of challenges for supply chain redesign
(Rosa et al., 2019a)	[20]	Examine the circular business model research context from all angles and inform businesses of it.	Support system for businesses, researchers, and governments to create circular business model
(Rosa et al., 2019b)	[21]	Identify the benefits that businesses expect from CE and reject them from a TBL viewpoint of sustainability.	Roadmap of PSS within WEEE
(Upadhyay et al., 2019)	[22]	Determine the specific factors affecting the service and manufacturing sectors, and evaluate how these affect the circular business model	Set of role types for circular business models
(Merli et al., 2018)	[23]	Defining the terms, ideas, and standards that companies should follow for CE	Framework of structural dimensions and analytic categories.

The Driver dimension (Table 23) explores, identifies, and analyses the variables and factors, external and internal, involved in the CE implementation (Hina et al., 2022), especially in food (Adams et al., 2021) and construction sector (Chen et al., 2022).

Environmental, economic, political, social, and health drivers are identified in agri-food sector, such as new job creation, reduced demand for virgin materials, attention to global warming, and laws and regulations that minimise environmental impacts of production and consumption (Mehmood et al., 2021).

A set of political (i.e., institutional and organisational legislation) and environmental directive drivers are the driving force for CE in food packaging (Tanveer et al., 2023) and textile and apparel industries (Jia et al., 2020). At the same time, social drivers (e.g., consumer consciousness of environmental pressure in the textile industry) increased customer awareness' of sustainable clothing consumption (Abbate et al., 2023; Aloini et al., 2020; Hugo et al., 2021). The main social driver is customer involvement, which explains the relation between customers and companies to meet demand (Mies and Gold, 2021), in the plastic packaging waste sector (Fogt Jacobsen et al., 2022). Customer demand, identified as market demand, drives the adoption of a circular business model (Assmann et al., 2023). Also, economic, environmental, regulatory, and organizational divers are enablers in implementing the circular business model (Foroozanfar et al., 2022). Hence, drivers are facilitators and factors in implementing circular strategies, such as reverse logistic practice (Silvério et al., 2023), which increased due to economic and strategic drivers (Mallick et al., 2023), enabling circular manufacturing to achieve sustainability (Acerbi and Taisch, 2020). Also, green chemistry is a circular driver for sustainability in the big pharma industry (Silvestri et al., 2021). Digital technologies (e.g., internet of things, big data, decision support tools based on data analytics tools) assumed the role of drivers in the CE transition (Acerbi et al., 2021). Further, these technologies are suitable to evaluate CE performance like indicators (Despeisse and Acerbi, 2022). It was possible to assess the close relation between drivers and indicators (Blüher et al., 2020). Drivers are useful in investigating the undesired effect of CE (Metic and Pigosso, 2022).

Table 23. Drivers dimension

References	n.	Objective	Output
(Assmann et al., 2023)	[24]	The factors influencing or impeding the adoption of circular business model	Map of eight macro categories for circular business model adoption
(Metic and Pigosso, 2022)	[25]	Encourage the systematisation of CE-related RE research	Conceptual framework of RE
(Mallick et al., 2023)	[26]	Investigate if the actions, processes, key performance indicators (KPIs), and other factors driving the adoption and creation of reverse logistics are covered in the literature.	Conceptual framework for reverse logistic
(Abbate et al., 2023)	[27]	Present a summary of sustainability trends in the context of textile, apparel and fashion manufacturing	List of factors that influence and hinder the adoption of CE and corporate social responsibility standards
(Silvério et al., 2023)	[28]	Identify CE topics from a strategically competitive vantage point.	Framework for incorporating CE tactics into companies.
(Tanveer et al., 2023)	[29]	Determine how the levels of circularity are currently being applied in food packaging industry.	Framework for the identification of drivers, barriers, and levers in food packaging industry
(Fogt Jacobsen et al., 2022)	[30]	Examine the factors that cause and prevent customers from avoiding plastic packaging waste	Framework of drivers and barriers
(Hina et al., 2022)	[31]	Determine the factors that contribute to successful CE business model implementation.	Framework for looking into how drivers and barriers interact in CE business model
(Foroozanfar et al., 2022)	[32]	Identify the five main areas of interest when classifying the CE drivers used to simulate businesses.	Framework for CE business model and CE strategies
(Chen et al., 2022)	[33]	Identify the internal and external driving forces in the supply chain for construction.	Framework for circular construction
(Despeisse and Acerbi, 2022)	[34]	Examine how this area of production management systems research is addressing the issue of environmental sustainability.	Thematic framework for eco-efficient and circular industrial systems.
(Adams et al., 2021)	[35]	Research how food manufacturing companies integrate sustainability into their supply chains and operations	Checklist of eight key sustainability themes
(Hugo et al., 2021)	[36]	Determine the factors, practises, and limits that affect how CE ideas are implemented in the supply chain of the fashion industry.	Framework to summarise the initiatives, barriers, drivers, and actions
(Mies and Gold, 2021)	[37]	Examine the relationship between the academic CE and the social sustainability dimension.	Map of interrelations between social aspects and CE
(Silvestri et al., 2021)	[38]	Investigate the role of Green Chemistry in business	Basis for comprehending the role of the green chemistry in business from a sustainability and CE perspective
(Acerbi et al., 2021)	[39]	Determine and categorise the appropriate information and data needed to implement the circular manufacturing strategy.	Theoretical framework to connect 9R strategies and technologies
(Mehmood et al., 2021)	[40]	Identify the agri-food supply chain's driving factors and challenges.	Set of drivers in agri-food
(Blüher et al., 2020)	[41]	Determine and study sustainability impacts in PSS about their interactions.	Correlation map between drivers and indicators in PSS
(Acerbi and Taisch, 2020)	[42]	Highlight the CE tactics used in the manufacturing industry.	Set of circular manufacturing strategies
(Aloini et al., 2020)	[43]	Identify and categorise the main drivers behind and critical success factors for CE initiatives.	Theoretical framework of drivers and critical success factors
(Jia et al., 2020)	[44]	Discover on the status of the sustainable supply chain management research towards a CE in the textile and apparel industry at this time.	Conceptual framework to relate drivers and performance to CE practices

The Circular manufacturing ecosystem dimension (Table 24) focuses on the remanufacturing process, which has been added to reduce, reuse, and recycle practices and obtain new materials and energies from resources (Acerbi and Taisch, 2020). The domain investigates all the actors and activities involved in the complex network (Ada et al., 2023), from raw materials to be delivered and returned (L. Ding et al., 2023).

LCAs are used to examine the environmental impact generated in the supply chain of the textile (Amicarelli et al., 2022) and food packaging industries (Kakadellis and Harris, 2020).

Information sharing promoted CE adoption to keep materials in a closed loop, and the information flow across the whole supply chain supported by technology (Jäger-Roschko and Petersen, 2022). In fact, digital technologies, particularly cloud service, artificial intelligence, big data analytics, internet of things, and blockchain technology (Sood et al., 2022), are enablers to digitalise the sustainable supply chain. These technologies are also advantageous for decision making processes related to environmental, economic, and social issues (Liu et al., 2023). 3D printing technology plays a strategic role in reuse, recycling, and remanufacturing activities (Marić et al., 2023). Technologies for sustainability, among which design for disassembly and additive manufacturing, information systems, and internet of things are implemented in Singapore to reach zero waste manufacturing (Kerdlap et al., 2019).

Table 24. Circular manufacturing ecosystem dimension

References	n.	Objective	Output
(Ada et al., 2023)	[45]	Detect and analyse circularity-related issues with food packaging	Framework to relate CE principles, packaging materials, and the food sub-sector
(Liu et al., 2023)	[46]	Examine how the informational and digital technologies indicated in Industry 4.0 improves supply networks' physical and cyber capabilities and promotes sustainable supply chain management from the perspective of CE.	Framework characterised by five technologies
(L. Ding et al., 2023)	[47]	Examine supporting data from articles on CE that address certain forward or reverse logistic operations in the construction project life cycle.	Framework and associated/possible circular logistics integration mechanisms
(Marić et al., 2023)	[48]	Determine the main theoretical pillars and key research areas in the 3D printing technology field.	Map of eight research themes
(Sood et al., 2022)	[49]	Examine how Industry 4.0 enabling technologies are now being used	Guideline for implementing enhanced cyber-physical system for biological device simulation, monitoring, control, and feedback
(Jäger-Roschko and Petersen, 2022)	[50]	Recognise how improved sharing of data aids to keep materials and products in the loop	Framework of information sharing in CE
(Amicarelli et al., 2022)	[51]	Describe the environmental issues raised by the various stages of the textile production life cycle.	Set of environmental issues in various phases of the life cycles of fibres, yarns, and textiles
(Kakadellis and Harris, 2020)	[52]	This investigation aims to find possibilities and potential trade-offs within the food-packaging system.	Set of quantitative analyses for five LCA impact categories
(Kerdlap et al., 2019)	[53]	Recognise the most recent technological advancements in each zero-waste manufacturing subject and the obstacles to implementation in order to realise zero waste manufacturing 's objectives in the world's most urbanised areas.	Six technology themes

The PLM dimension (Table 25) deals with every stage across the entire lifetime in a CE way (De Oliveira et al., 2021). PLM is in continuous evolution due to modern technologies (e.g., 3D printing and cloud service) (Conlon, 2020). Indeed, various aspects of PLM software are influenced by big data analytics and the internet of things (Sakao and Nordholm, 2021). These technologies make it possible to obtain information and user-data to benefit consumers, businesses, and other stakeholders (Brandt et al., 2021; Meyer et al., 2021). The information gathered was valuable in supporting items in repair or maintenance before retirement (Barrios et al., 2022), particularly in adapting the life cycle of traditional products through remanufacturing (Li et al., 2021a).

In the PLM stages, validation and verification are two processes that focus on checking the cycle progression and addressing the customers' requests (Karkasinas and Rentizelas, 2019). Another ability of PLM to track the progress of a product throughout its life cycle and get information is traceability (Corallo et al., 2020).

PLM has also been closely related to business model, in particular PSS (Reim, 2013; Sassanelli et al., 2019b).

Table 25. Product lifecycle management dimension

References	n.	Objective	Output
(Barrios et al., 2022)	[54]	Analyse how PLM and internet of things are related.	Framework for combining PLM and internet of things
(De Oliveira et al., 2021)	[55]	Analyse the amount of research on topics connected to using technology from the Fourth Industrial Revolution to advance sustainable development and support PLM	Map to promote sustainable development using the technologies of the Fourth Industrial Revolution as inputs for PLM
(Li et al., 2021a)	[56]	Research and assessment of the life cycle management of remanufactured products	Framework of an integrated system with multiple product lifecycles for remanufacturing
(Meyer et al., 2021)	[57]	Enumerate the key principles, benefits, limiting aspects, and difficulties of using data-driven product planning	A collection of data-driver notions
(Brandt et al., 2021)	[58]	Analyse the state of the research on PSS business models and determine how it relates to strategy and tactics.	Topic map outlining how internet of things data from product scenarios is integrated into PLM information system
(Sakao and Nordholm, 2021)	[59]	Increase the understanding of PLM software to assist the industrial sector in being more environmentally sustainable.	Map of PLM information flow
(Corallo et al., 2020)	[60]	Investigate the connection between product lifetime and traceability	Map to explore the related concepts
(Conlon, 2020)	[61]	Comprehend how to conceptualise and imagine PLM in the fashion and textiles industry.	A methodology for identifying PLM's contribution to the digital transformation
(Sassanelli et al., 2019b)	[62]	Knowing how lean is applied in the PSS setting	Collection of lean applications under PSS
(Karkasinas and Rentizelas, 2019)	[63]	Research how to use Verification & Validation across the product lifecycle	Map of Verification & Validation process
(Reim, 2013)	[64]	Analyse existing PLM IS that facilitate the collection, storing, and analysis of product lifecycle data to determine the advantages and difficulties	Framework for integrating tactics, business models, and strategy

The Socio-economic aspects dimension (Table 26) explores in detail the different macro-levels that CE affects, such as people's choices (e.g., worker, customer) (Mies and Gold, 2021). In the 9Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) framework, which used to involve only resources, the R dimension of Rethink is expanded to include socioeconomic aspects (Valencia et al., 2023).

Social sustainability gained more attention due to the impact of customers' behaviour in choosing a product (e.g., packaging and food) on enhancing economic sustainability (Kumar et al., 2022; Pålsson and Olsson, 2023). Digital technologies are used to produce innovative sustainable circular products in line with customer needs (Agrawal et al., 2022).

Table 26. Socio-economic aspects dimension

References	n.	Objective	Output
(Pålsson and Olsson, 2023)	[65]	Analyse existing knowledge to determine if reusable or disposable packaging is more environmentally friendly and circular in various situations and for various product kinds.	A map of articles comparing reusable versus disposable food, drink, and e-commerce packaging
(Valencia et al., 2023)	[66]	Learn the sociological aspects of achieving a CE within the limits of the planet	A framework to find Rs for the CE with a strong sustainability standpoint
(Agrawal et al., 2022)	[67]	Conduct a network-based analysis on the relationship between CE and successful sustainable company operations in the context of digitalization	A set of information to combine CE and sustainable business performance from the viewpoint of digitalization
(Kumar et al., 2022)	[68]	Create a thematic synthesis of the literature on the sustainable food supply chain and identify the major areas for future stud.	A list of the nine major topics from the sustainable food supply chain research

The relationships among the five CE dimensions were identified in some of the analysed papers and are represented here through the proposed conceptual maps. Figure 12 and Figure 13 show these maps, grouped in clusters based on the detected relations, highlighting that not all factors are interconnected.

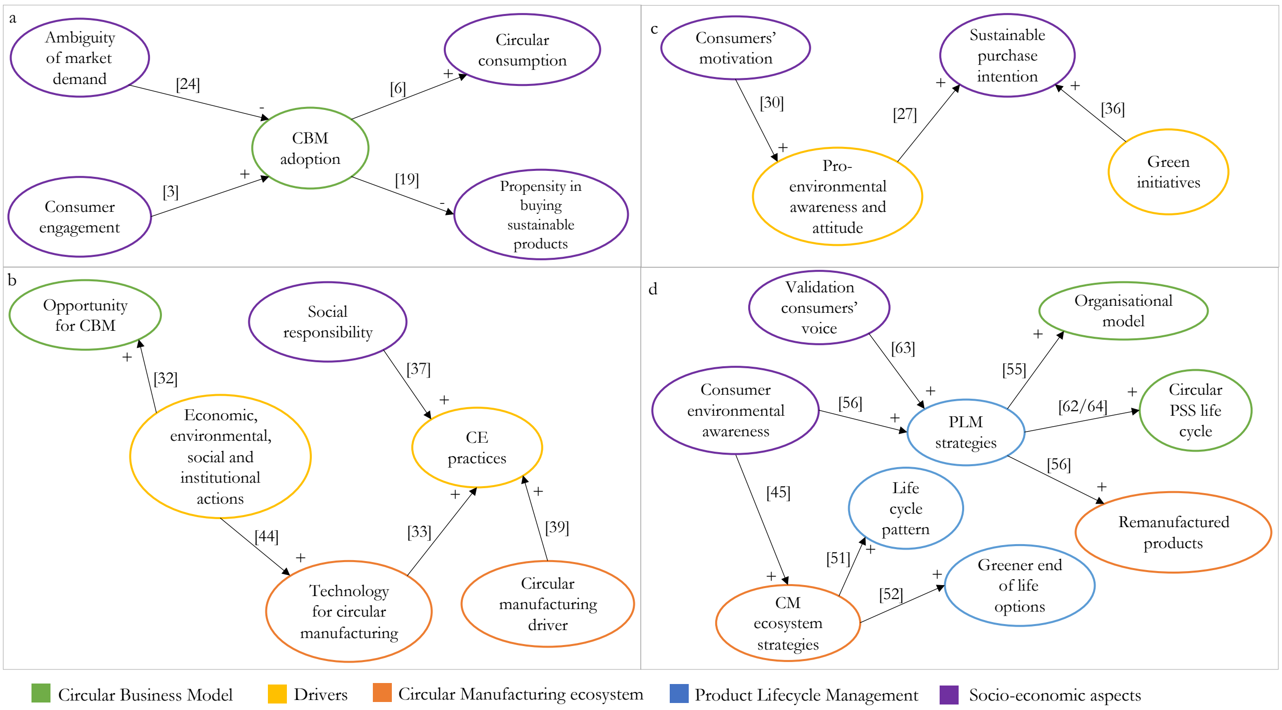


Figure 12. Conceptual map

In the first map shown in Figure 12a, it is possible to observe that the *circular business model adoption* promotes the propensity towards *circular consumption* choices (link n. [6]) due to the circular mindset. This leads to sustainable material choices in line with conservation and value creation (Gomes et al., 2022). *Consumer engagement* leads to a higher *circular business models adoption* to achieve sustainability (link n. [3]), following the interest in obtaining environmental benefits in consumer situations (De Bruyne and Verleye, 2023). The *ambiguity of market demand* is a driving force behind the *circular business model adoption* (link n. [24]) to cope with uncertainty and negative consumer attitudes (Assmann et al., 2023). The *circular business model adoption* causes a negative effect on consumer *propensity to buy sustainable products* (link n. [19]) due to the cost and the idea of a second-hand product (Bressanelli et al., 2019).

In Figure 12b, *economic, environmental, social, and institutional actions* are the driving forces in bringing about a new *opportunity for circular business model* (link n. [32]), as they promote efforts to avoid the use of scarce resources, make businesses from waste, create awareness about sustainability to regulate environmental risks, and encourage the adoption of environmentally friendly technologies (Foroozanfar et al., 2022). These drivers, *economic, environmental, social, and institutional actions*, promote the adoption of *technology for circular manufacturing* (link n. [44]) for innovative practices (Jia et al., 2020). The use of *technology for circular manufacturing* (e.g., the Internet of Things and information systems) promotes the implementation of *CE practices* (link n. [33]) through industrial symbiosis (Chen et al., 2022). *Circular manufacturing driver* strategies push to achieve these *CE practices* (link n. [39]) because of their role in supporting cleaner production and the use of renewable energy sources (Acerbi et al., 2021). *Social responsibility* drives the adoption of *CE practices* (link n. [37]) by choosing to buy products at a higher cost to support recycling activities and the return of end-of-life products (Mies and Gold, 2021).

In Figure 12c, *consumer motivation* generates *pro-environmental awareness and attitude* (link n. [30]), particularly towards the use of recycled materials for packaging (Fogt Jacobsen et al., 2022). This *pro-environmental awareness and attitude* lead consumers to have a more *sustainable purchase intention* (link n. [27]), such as eco-sustainable, recycled, or used products (Abbate et al., 2023). The presence of *green initiatives* in textile firms generates more *sustainable purchase intention* (link n. [36]) among consumers because they want to support sustainable causes and prefer products that pollute less (Hugo et al., 2021).

In Figure 12d, *PLM strategies* become a tool to implement and plan creative and resilient *organisational models* (link n. [55]) to achieve sustainability and cope with uncertain scenarios (De Oliveira et al., 2021). *PLM strategies* influence the circular business model phases, integrating them into the *circular PSS life cycle* (link n. [62/64]) (Reim, 2013; Sassanelli et al., 2019b). *Validation consumers' voice* is a necessary practice to adopt the correct *PLM strategies* (link n. [63]) and identify consumer opinions and preferences (Karkasinas and Rentizelas, 2019). *Consumers environmental awareness*, which promotes green initiatives, influences the increasing implementation of *PLM strategies* (link n. [56]), which allow the production of remanufacturing products according to their sustainable demand (Li et al., 2021a). *Consumer environmental awareness*, particularly regarding the use of plastics in packaging, also generates and influences the adoption of *circular manufacturing ecosystem strategies* (link n. [45]) (Ada et al., 2023), which have a positive impact on the *life cycle pattern* (link n. [51]) of products to achieve environmental benefit (Amicarelli et al., 2022), particularly on *greener EoL options* (link n. [52]), such as anaerobic digestion and composting for the food industry (Kakadellis and Harris, 2020).

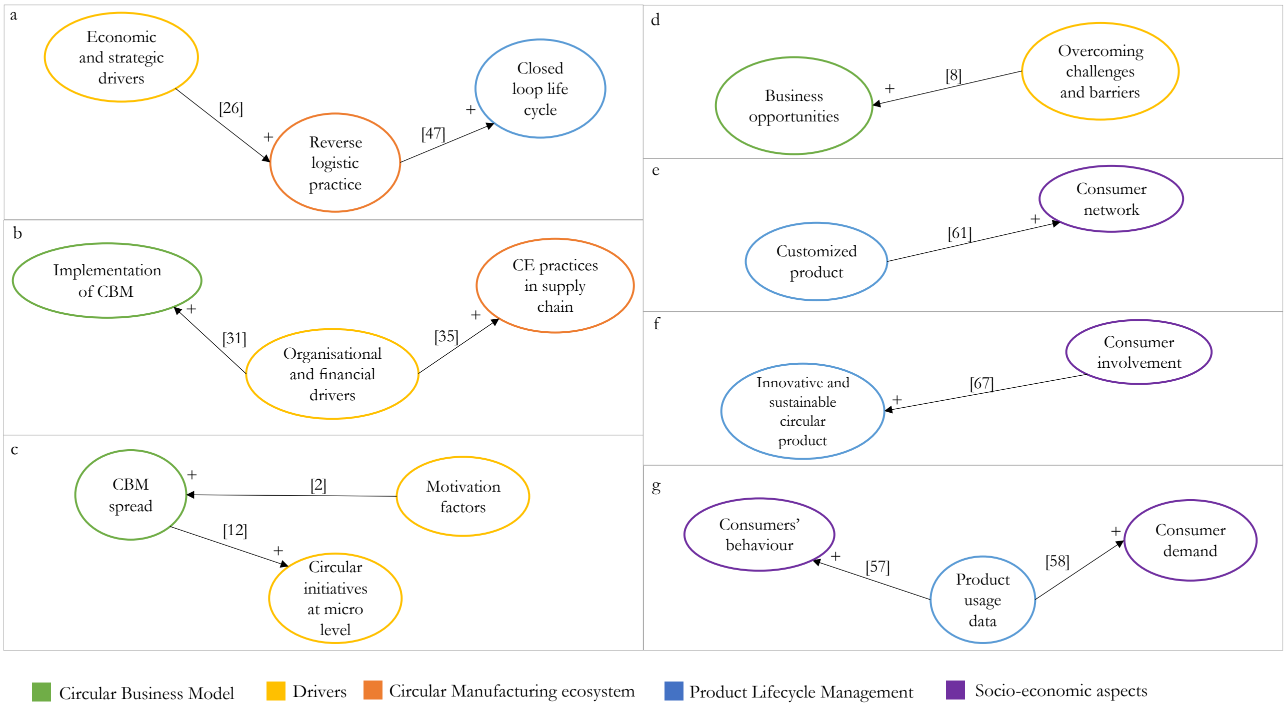


Figure 13. Conceptual map

In Figure 13a, *economic and strategic drivers*, identified as decreasing production costs or reducing energy consumption, drive and influence the application of positive *reverse logistic practice* (link n. [26]) (Mallick et al., 2023), which supports a *closed loop life cycle* for products (link n. [47]) as the counterpart of forward logistics in the logistic system (L. Ding et al., 2023). In Figure 12b, *organisational and financial drivers* stimulate and motivate the *implementation of circular business model* (link n. [31]) from the inside through good leadership, design strategies, innovation, research, and development (Hina et al., 2022). *Organisational and financial drivers*, which includ management values, cost reductions, regulations, and social issues, influence the adoption of positive *CE practices in supply chain* (link n. [35]) to reduce waste (Adams et al., 2021).

In Figure 13c, *motivational factors* represent the reasons for companies to change and develop new business model; in fact, these factors accelerate and drive the *circular business model spread* (link n. [2]) in the long term (Försterling et al., 2023), generating more *circular initiatives at the micro level* (link n. [12]) in the electrical and electronics industry, the construction industry, and the manufacturing of wood, furniture, and paper that determine the willingness and need of firms to adopt sustainable solutions (Mhatre et al., 2021).

In Figure 13d, the interest in *overcoming challenges and barriers* related to logistics costs, infrastructure limitations, lack of financial resources and motivation, competitiveness, and inadequate regulation leads to the development of more *business opportunities* (link n. [8]) following economic, technological, and strategic drivers (Salvador et al., 2022).

In Figure 13e, a more digital PLM pays attention to the realisation of *customized products* that influence the *consumer network* (link n. [61]) by placing it at the centre of the production process (Conlon, 2020).

In Figure 13f, *consumer involvement* in sustainability actions produces an *innovative and sustainable circular product* (link n. [67]) that can be more easily returned after use (Agrawal et al., 2022).

In Figure 13g, the *product usage data* is collected to learn about *consumers' behaviour* (link n. [57]) and preferences, identify their requests and needs, and thus predict their *consumer demand* (link n. [58]) (Brandt et al., 2021; Meyer et al., 2021).

Table 27 summarises the links among the five dimensions, with rows representing origin dimensions and columns representing destination dimensions.

Table 27. Summary of the relations detected between the five dimensions

	Circular Business model	Drivers	Circular manufacturing ecosystem	Product lifecycle management	Socio-economic aspects
Business model	-	5	0	1	4
Drivers	4	-	4	0	3
Circular manufacturing ecosystem	0	4	-	4	1
Product lifecycle management	2	0	3	-	6
Socio-economic aspects	1	3	1	4	-

The Business model dimension had five relations with drivers, four with Socio-economic factors, and one with PLM. The Driver dimension is correlated with the Circular manufacturing ecosystem and Business model four times and with Socio-economic aspects three times. The factors of the Circular manufacturing ecosystem are related to Drivers and PLM four times and to Socio-economic aspects just once. The PLM dimension is linked to Socio-economic factors six times, three times to the Circular manufacturing ecosystem, and twice to Business model. The Socio-economic aspects dimension had four relations with PLM, three with Drivers, and one with the Circular manufacturing ecosystem and Business model.

Every dimension has at least a relation with three others, with the exception of the Socio-economic aspects dimension, which is linked to all four of them. It is noteworthy that the Socio-economic dimension is the only one that has any connection to the other four, as it focuses on the individual's engagement and the social role of the CE. The focus was on the individual, taking on the role of the client. As the client has the option to accept circular products, it is his perspective that contributes to making sustainability achievable. Specifically, consumer behaviour and preferences take the stage.

The Business model dimension is unrelated to the Circular manufacturing ecosystem due to a lack of implementation of reuse and remanufacturing techniques in business models. Additionally, the Driver dimension had no effect on PLM by not connecting the two dimensions together.

The PLM and Socio-economic aspects dimensions are closely related, although most of the clusters involving this relation are not multiple.

The customer is involved at every stage of the product lifecycle, from development and customisation to end-of-life. Business model and Driver dimensions are also correlated in clusters composed of single links. At this purpose, it has to be highlighted that only the Circular manufacturing ecosystem—which combines a variety of actors and variables for the reuse of resources and energy—lacks a direct single link with the Socio-economic aspect dimension. Multiple relations are presented concurrently, and the factors involved in these relations could constitute the critical factors, referred to as such due to the number of connections and the dimensions concerned. A critical factor is the PLM dimension factor in Figure 11d. The factor *PLM strategies* is the effect of a positive link with two factors in the Socio-economic dimension (*consumer environmental awareness* and *validation consumers' voice*) and also leads to two factors in the Business model dimension (*organisational model* and *circular PSS life cycle*) and to one in the Circular manufacturing ecosystem (*remanufactured products*). Therefore, several dimensions are influenced by the *PLM strategies* factor and conditioned by how it is implemented.
As shown in Figure 12 and Figure 13, each factor in a multiple interaction takes on a role, either as a cause or an effect, but not exclusively. Several factors played two roles—cause and effect, or vice versa, where the cause represents the origin of the relation, and the effect is the destination. One example is *technology for circular manufacturing* (Figure 11b), which is an effect of economic, environmental, social, and institutional initiatives but is also a driver of CE practices. The *circular manufacturing ecosystem strategies* (Figure 11d) played two roles: firstly, they influence products in the PLM dimension, and, secondly, they are shaped by a socio-economic component. *Reverse logistic practices* (Figure 12a) were driven by constructive tactics and encouraged to use PLM techniques like closed loop. It is evident that several elements of the Circular manufacturing ecosystem played distinct roles in the process of achieving circularity.
The factors of the different links have been grouped according to the circular aspect pursued. In fact, Figure 11a presents all factors about the Socio-economic aspects influenced by the adoption of circular business model. Figure 11b depicts how technology promotes circularity in manufacturing as an enabling factor. In Figure 11c, socio-economic aspects are central to their role as enhancers of CE implementation. In Figure 11d, the focus is on *PLM strategies* in society to achieve sustainability. Three macro groups have been identified in Figure 12. Figures 12a and 12b present the involvement of manufacturing companies in circular strategies. Figures 11c and 11d focus on the role of circular business model as a driver of CE implementation. Figures 12e, 12f, and 12g highlight the connections between PLM strategies and socio-economic aspects.

Although the conceptual maps in Figure 12 and Figure 13 highlight the benefits of CE implementation and the interactions among the five dimensions, these same interconnections can also give rise to negative consequences. To systematically analyse this potential, the links identified in the maps have been classified in Table 28 according to the four types of REs (i.e., direct, indirect, economy-wide, and transformational). Each link has been assigned to a RE type based on the effect it could potentially generate, allowing the clustered classification to reflect the patterns and pathways previously visualized in the maps.

Table 28. RE classification

Dimension / RE type	Business model	Drivers	Circular manufacturing ecosystem	Product lifecycle management	Socio-economic aspects	n.	Cluster
Direct	Circular business model adoption (**D**)				Consumer engagement (**O**)	[3]	11a
	Circular business model adoption (**O**)				Circular consumption (**D**)	[6]	11a
	Circular business model spread (**O**)		Circular initiatives at micro level (**D**)			[12]	12c
	Circular business model adoption (**O**)				Propensity in buying sustainable products (**D**)	[19]	11a
		Pro-environmental awareness and attitude (**O**)			Sustainable purchase intention (**D**)	[27]	11c
		Pro-environmental awareness and attitude (**D**)			Consumers' motivation (**O**)	[30]	11c
		Green initiatives (**O**)			Sustainable purchase intention (**D**)	[36]	11c
				PLM strategies (**D**)	Consumer environmental awareness (**O**)	[56]	11d
				Customized product (**O**)	Consumer network (**D**)	[61]	12e
Total	**O**: 3 **D**: 1	**O**: 2 **D**: 1	**O**: 0 **D**: 1	**O**: 1 **D**: 1	**O**: 3 **D**: 5		
Indirect	Circular business model adoption (**D**)				Ambiguity of market demand (**O**)	[24]	11a
		CE practices (**D**)			Social responsibility (**O**)	[37]	11b
		CE practices (**D**)	Circular manufacturing driver (**O**)			[39]	11b
			Circular manufacturing ecosystem strategies (**D**)		Consumer environmental awareness (**O**)	[45]	12d
			Reverse logistic practice (**O**)	Closed loop life cycle (**D**)		[47]	12a
			Circular manufacturing ecosystem strategies (**O**)	Life cycle pattern (**D**)		[51]	11d
			Circular manufacturing ecosystem strategies (**O**)	Greener EoL options (**D**)		[52]	11d
				Product usage data (**O**)	Consumers' behaviour (**D**)	[57]	12g
				Product usage data (**O**)	Consumer demand (**D**)	[58]	12g

				PLM strategies (**D**)	Validation consumers' voice (**O**)	[63]	12d
				Innovative and sustainable circular product (**D**)	Consumer involvement (**O**)	[67]	12f
Total	**O**: 0 **D**: 1	**O**: 0 **D**: 2	**O**: 4 **D**: 1	**O**: 2 **D**: 5	**O**: 5 **D**: 2		
Economy-wide		Economic and strategic drivers (**O**)	Reverse logistic practice (**D**)			[26]	12a
		CE practices (**D**)	Technology for circular manufacturing (**O**)			[33]	11b
		Organisational and financial drivers (**O**)	CE practices in supply chain (**D**)			[35]	12b
		Economic, environmental, social and institutional actions (**O**)	Technology for circular manufacturing (**D**)			[44]	11b
			Remanufactured products (**D**)	PLM strategies (**O**)		[56]	11d
	Circular PSS life cycle (**D**)			PLM strategies (**O**)		[62/64]	11d
Total	**O**: 0 **D**: 1	**O**: 3 **D**: 1	**O**: 1 **D**: 4	**O**: 2 **D**: 0	**O**: 0 **D**: 0		
Transformational	Circular business model spread (**D**)	Motivation factors (**O**)				[2]	12c
	Business opportunities (**D**)	Overcoming challenges and barriers (**O**)				[8]	12d
	Implementation of circular business model (**D**)	Organisational and financial drivers (**O**)				[31]	12b
	Opportunity for circular business model (**D**)	Economic, environmental, social and institutional actions (**O**)				[32]	11b
	Organisational model (**D**)			PLM strategies (**O**)		[55]	11d
Total	**O**: 0 **D**: 5	**O**: 4 **D**: 0	**O**: 0 **D**: 0	**O**: 1 **D**: 0	**O**: 0 **D**: 0		
TOTAL FOR ALL RE DIMENSIONS	**O**: 3 **D**: 8	**O**: 9 **D**: 4	**O**: 5 **D**: 6	**O**: 6 **D**: 6	**O**: 8 **D**:7		

In Table 28, the first rows mapped CE relations that could lead to a direct RE (i.e., those directly involving the consumer or producer (micro-level)). Looking at the link [3], the *consumer engagement* that led to *circular business model adoption* may have unfavourable effects due to their potential to impact market demand and increase the consumption of one product. The *circular business model adoption* generates *circular consumption* and could lead to a direct effect due to the possibility of increasing consumption of the same products as a possible result of an income mechanism (link [6]). The link [12] between *circular business model spread* and *circular initiatives at micro level* could lead to an improvement in the price, production, or perception of a product and raise its demand or consumption. The *circular business model adoption* correlated to the *propensity in buying sustainable products* (link [19]), and the *pro-environment awareness and attitude* related to *sustainable purchase intention* (link [27]) could increase their demand due to the perceived sustainability benefits generated by motivational and sufficiency mechanisms. The *consumers' motivation*, which has generated *pro-environment awareness and attitude*, could lead to a higher demand for the same product than expected due to the change in consumer perception following the motivational mechanism (link [30]). *Green initiatives* drive *sustainable purchasing intentions* and could increase the consumption of a certain product due to an improvement, possibly in line with circular strategies, caused by output and time mechanisms (link [36]). *Consumer environmental awareness* linked to *PLM strategies* that involve efficiency in product manufacturing could lead to higher demand for that product because of the improvement in production probably generated by the output mechanism (link [56]). *Customized products* correlated to the *consumer network* could change consumer preferences and lead to higher demand for the same products, following the motivational mechanism (link [61]).

An indirect effect could occur in links involving consumer or producer actions and the whole market of interest. Indeed, the links [24] between *ambiguity of market demand* and *circular business model adoption* could potentially bring about an efficiency improvement to one product while changing the demand or supply for other products. *Social responsibility* led to *CE practices* that could change the consumer's perception of a product and enhance demand for others, as in a motivational mechanism (link [37]). *Circular manufacturing driver* correlated to *CE practices* could generate a re-investing mechanism, reducing production costs and increasing the supply of other products (link [39]). The link [45] between *consumer environmental awareness* and *circular manufacturing ecosystem strategies* could lead to an improvement in the production or consumption of a product, possibly leading to higher consumption of other products. *Reverse logistic practice* in a *closed loop life cycle* could generate an efficiency improvement in resource costs while increasing consumption of other resources, causing a substitutional mechanism (link [47]). *Circular manufacturing ecosystem strategies* related *to life cycle pattern* could generate an efficiency improvement in production, which could increase demand or supply for other products (link [51]). A *Circular manufacturing ecosystem* linked to *greener EoL options* could generate an imperfect substitutional mechanism because secondary goods may be of lower quality, thus increasing consumption of primary goods (link [52]). The connection between *product usage data* and *consumers' behaviour* could cause a motivational mechanism where consumer preferences and perceptions could change, leading to higher consumption of other products (link [57]). *Product usage data* influenced *consumer demand*, probably reducing the cost of a product and increasing demand for others, generating a re-spending mechanism (link [58]). *Validation consumers' voices* related to *PLM strategies* could lead to a motivational mechanism due to a switch in consumer preferences that could cause higher consumption of other goods (link [63]). The link [67] between *consumer involvement* and *innovative and sustainable products* could cause an imperfect substitution mechanism because the new product made of secondary goods could be of inferior quality, increasing consumption of primary products.

Economy-wide refers to both direct and indirect effects and evaluates the map links that involve interrelations between consumers and producers in a macro scenario, such as cities, regions, and nations. Among the links, *economic and strategic drivers* related to *reverse logistic practice* could generate a composition mechanism because an efficiency improvement in production could reduce prices and consequently increase demand (link [26]). *Technology for circular manufacturing* led to *CE practices*, which could cause efficiency in the market with changes in demand or supply (link [33]). The link [35] between *organisational and financial drivers* and CE practices in the supply chain could shift the production pattern, leading to higher resource consumption, as in a structural change mechanism. *Economic, environmental, social, and institutional actions* led to improvements in *technology for circular manufacturing*, which could enhance production factors, leading to higher demand and boosting economic growth as a cross-factor mechanism (link [44]). *PLM strategies* related to *remanufactured products* could bring about a resource market mechanism, where, due to an efficiency improvement in resource use, prices could reduce, and demand could rise (link [56]). *PLM strategies* also led to the implementation of a *circular PSS life cycle*, which could generate structural change mechanisms that could improve production patterns while increasing consumption (link [62/64]).

Transformational effects could arise in links that involve efficiency improvement on a large scale in the economy and society. In this effect, *motivational factors* accelerated the *circular business model spread* because it could represent a big change for the whole society (link [2]). *Overcoming challenges and barriers* drove new *business opportunities* and could improve and modify economic patterns in the entire society (link [8]). *Organisational and financial drivers* associated with *implementation of circular business model* could lead to efficiency improvements for a large system (link [31]). Also, *economic, environmental, social, and institutional actions* led to new *opportunity of circular business model* that could influence the entire economy, the organisation of production, and consumer preferences (link [32]). The link [55] between *PLM strategies* and *organisational models* could generate an efficiency improvement that influences not only the economic category but also the whole economy and society.

Summarising, mostly direct effects could be generated in the Business model and Socio-economic aspect dimensions Specifically, five destination factors were identified in the Socio-economic dimension, while three origin factors were primarily detected in the Business model and Socio-economic aspect dimensions. Thus, to prevent and mitigate undesirable direct effects, it must operate in a circular business model implementation and carefully assess its impact on social aspects, particularly consumer perception.

The indirect effects could be generated from the Socio-economic aspect dimension to the PLM dimension, where five factors of origin were pinpointed for the first dimension and five of destination for the second one. In this case, it must take care of managing consumer actions that might influence the demand or supply of other goods due to an efficiency improvement in one product, as observed in the PLM dimension.

To prevent the occurrence of economy-wide effects, the dimensions where these effects could be most generated are Drivers and the Circular manufacturing ecosystem, where could be involved more complex dynamics of demand and supply. Thus, it could operate in drivers that stimulate higher demand or consumption, with three identified origin factors, and in circular manufacturing practices that generate efficiency, with four detected destination factors, probably with negative consequences.

Lastly, the transformation effect could arise in the Driver and Business model dimensions. Therefore, proactive measures should be taken in the two dimensions to prevent unexpected changes in the entire economy and society. Four source factors were identified in the Driver dimension, and five destination factors in the Business model dimension were became the two main dimensions to investigate.

In general, RE could be generated in all five dimensions with different magnitudes. The dimension with the highest number of origin and destination factors is Socio-economic aspects, with an amount of 15 factors focusing on consumers' roles and their circular actions. While nine origin factors were detected in the Drivers' dimension and eight destination factors in the Business model dimension, explaining how these dimensions may cause RE and pointing out where attention should be placed to prevent and avoid the negative consequences. Meanwhile, the Circular manufacturing ecosystem and PLM dimensions involve fewer factors that may generate RE.

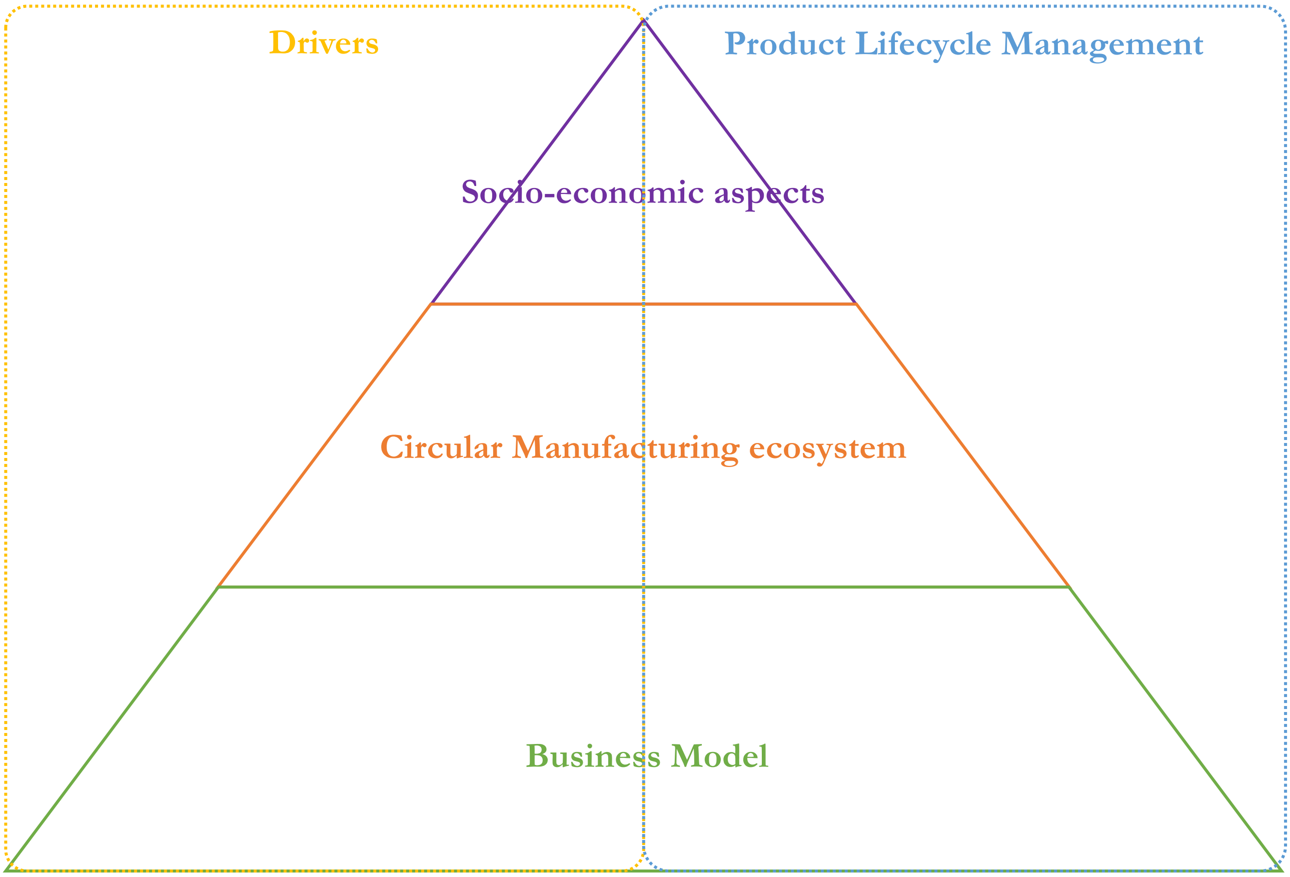


Figure 14. Five dimensions across different conceptual level

Finally, Figure 14 depicts the five dimensions considered (i.e., Business model, Circular manufacturing ecosystem, Socio-economic aspects, PLM, and Drivers) showing how they operate at different conceptual levels yet remain interconnected within a unified system. Their arrangement in a pyramid highlight not only their hierarchical positioning but also their functional dependencies.

At the base of the pyramid, the Circular business model dimension represents the organisational level. It defines how a firm structures value creation, delivery, and capture when adopting circular strategies. This foundational role is visualised through its placement at the bottom, indicating that business model decisions influence—and are influenced by—all the other dimensions.

Situated above it is the Circular manufacturing ecosystem, operating at the inter-organisational level. This dimension encompasses the network of suppliers, partners, service providers, and other actors necessary to implement circular strategies in practice. Its placement directly above the business model reflects the mutual relationship between the two: business model choices shape ecosystem configuration, while ecosystem capabilities and collaborations determine which business models are feasible.

The next level includes Socio-economic aspects, which represent the broader contextual environment in which organisations and ecosystem's function. These include regulatory frameworks, cultural norms, market conditions, and institutional structures. Their position in the middle of the pyramid illustrates their role as a boundary-setting layer that both constrains and enables circular practices at organisational and ecosystem levels.

At the upper corners of the pyramid are PLM and Drivers, both of which act as cross-cutting dimensions. The PLM dimension structures decisions across the entire life cycle of a product, design, production, use, maintenance, and end-of-life, and is directly linked to ecosystem capabilities, business model logic, and socio-economic constraints. While the Drivers dimension includes technological innovations, regulatory pressures, market forces, and societal trends. These factors exert influence across all levels of the pyramid, shaping business models, ecosystem configurations, socio-economic conditions, and product strategies.

Taken together, the pyramid conveys that these five dimensions cannot be treated as conceptually equivalent or isolated categories. Instead, they form a multi-level system in which each dimension plays a distinct role: Circular business models and Circular manufacturing ecosystems provide the structural and relational foundations; Socio-economic aspects shape the context; and PLM and Drivers introduce cross-level forces that interact with every other dimensions. This representation clarifies why the dimensions were selected and how they contribute collectively to understanding circular manufacturing ecosystem dynamics.

4.2.2 Developing the reference model

The conceptual maps served as a basis for developing the reference model.

Building on these maps, the first step involved identifying the factors that compose the model. Each new factor, building upon the old ones proposed in the initial reference model (i.e., the conceptual maps), was formulated to include of two components: an element (corresponding to one of the five dimensions of CE-RE: Business model, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects) and an attribute that specifies its connection with other factors.

For instance, the factor n. 9 *overcoming challenges and barriers* became *numbers of overcoming challenges and barriers.* It has been linked to the new factor n. 2 *level of opportunities in organisational model* pertaining (Salvador et al., 2022).In addition, the value of the attribute is characterised through the use of symbols ("+" or "-"), which are placed at the edge of the linking arrows. As an example, the factor n. 32 *validation consumers' voice* was reformulated as *level of validation of consumer voice.* A lower *level of validation of consumer voice* creates a higher *number of PLM strategies* (factor n. 17) in the PLM dimension (Karkasinas and Rentizelas, 2019), as the demand for consumer validation increases the need for solutions to monitor a product life cycle (Figure 15).

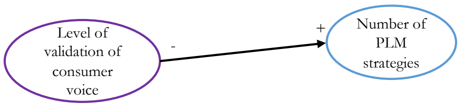


Figure 15. Graphical representation of a link

Table 29 details the evolution of factors from the initial conceptual maps to the final reference model, following the steps presented in the methodology. The first column lists the dimension of the RE of CE to which the factors are related. The second one reports the factors as they appeared in the conceptual maps. Then, in the third column, the new factors were reformulated as composed by an element plus an attribute. After this step, a further reformulation was needed to obtain the final reference model, as reported in the fourth column: some factors, being similar, were combined among them to constitute the final reference model factors (e.g., *types of circular business model adoption*, *types of implementation of circular business model*, *amount of circular business model spread* were merged into *amount of circular business model spread* (n. 1)). Finally, the last column indicates which are the key factors, success factors, and measurable success factors.

Table 29. List of factors included in the reference model

Dim	Initial reference model (conceptual maps) factors	Intermediate factors (reformulated as attribute + element)	Reference model factors	Type of factors
Business model	1. Circular business model adoption	1. Types of circular business model adoption	1. Amount of circular business model spread	1. Key factors
	1. Implementation of circular business model	1. Types of implementation of circular business model		
	1. Circular business model spread	1. Amount of circular business model spread		
	2. Organisational model	2. Type of organisational model	2. Level of opportunities in organisational model	
	2.Business opportunities	2. Level of business opportunities		
	3. Opportunity for circular business model	3. Quantity of opportunity for circular business model	3. Quantity of opportunity for circular business model	
	4. Circular PSS life cycle	4. Circularity of PSS life cycle	4. Circularity of PSS life cycle	
Drivers	5. Pro-environmental awareness and attitude	5. Level of pro-environmental awareness and attitude	5. Level of pro-environmental awareness and attitude	
	6. CE practices	6. Number of CE practices	6. Number of CE practices	
	7. Economic and strategic drivers	7. Numbers of economic and strategic drivers	7. Number of TBL, organizational, and institutional drivers and actions	7. Key factors
	7. Organisational and financial drivers	7. Numbers of organisational and financial drivers		
	7. Economic, environmental, social and institutional actions	7. Numbers of economic, environmental, social and institutional actions		
	8. Motivation factors	8. Types of motivation factors	8. Types of motivation factors	
	9.. Overcoming challenges and barriers	9. Numbers of overcoming challenges and barriers	9. Numbers of overcoming challenges and barriers	
	10. Green initiatives	10. Numbers of green initiatives	10.Numbers of green initiatives	10. Measurable Success Factors
	11. Circular initiatives at micro level	11. Types of circular initiatives at micro level	11. Types of circular initiatives at micro level	
Circular manufacturing ecosystem	12. CE practices in supply chain	12. CE practices in supply chain	12. CE practices in supply chain	
	13. Circular manufacturing driver	13. Types of circular manufacturing driver	13. Types of circular manufacturing drivers and strategies	13. Key factors
	13. Circular manufacturing ecosystem strategies	13. Types of circular manufacturing ecosystem strategies		
	14. Reverse logistic practice	14. Quality of reverse logistic practice	14. Quality of reverse logistic practice	14. Measurable Success Factors
	15. Technology for circular manufacturing	15. Types of technology for circular manufacturing	15. Types of technology for circular manufacturing	

	16. Remanufactured products	16. Quality of remanufactured products	16. Quality of remanufactured products	16. Success Factors
PLM	17. PLM strategies	17. Number of PLM strategies	17. Number of PLM strategies	17. Key factors
	18. Customized product	18. Types of customized product	18. Types of customized innovative and sustainable circular product	
	18. Innovative and sustainable circular product	18. Numbers of innovative and sustainable circular product		
	19. Closed loop life cycle	19. Quantity of closed loop life cycle	19. Quantity of closed loop life cycle	19. Success Factors
	20. Life cycle pattern	20. Types of life cycle pattern	20. Types of life cycle pattern	
	21. Greener EoL options	21. Quality of greener EoL options	21. Quality of greener EoL options	
	22. Product usage data	22. Quality of product usage data	22. Quality of product usage data	
Socio-economic aspects	23. Consumer engagement	23. Level of consumer engagement	23. Level of consumer involvement	
	23. Consumer involvement	23. Level of consumer involvement		
	24. Circular consumption	24. Level of circular consumption	24. Level of circular consumption	24. Success Factors
	25. Propensity in buying sustainable products	25. Propensity in buying sustainable products	25. Level and propensity of sustainable purchase intention	25. Success Factors
	25. Sustainable purchase intention	25. Level of sustainable purchase intention		
	26. Consumers' motivation	26. Level of consumer motivation	26. Level of consumer motivation	
	27. Consumer environmental awareness	27. Level of consumer environmental awareness	27. Level of consumer environmental awareness	
	28. Consumer network	28. Amount of consumer network	28. Amount of consumer network	
	29. Ambiguity of market demand	29. Ambiguity of market demand	29. Quantity and ambiguity of market demand	
	29. Costumer demand	29. Quantity of consumer demand		
	30. Social responsibility	30. Level of social responsibility	30. Level of social responsibility	
	31. Consumers' behaviour	31. Level of consumers' behaviour	31. Level of consumers' behaviour	
	32. Validation consumers' voice	32. Level of validation of consumer voice	32. Level of validation of consumer voice	

In particular, the factor n. 1 *amount of circular business model (circular business model) spread* is a core factor due to its seven connections, three with the Drivers dimension and four with the Socio-economic aspects dimension. This result highlights how the implementation of circular business model is driven by different factors, including motivational (Försterling et al., 2023), institutional, organizational (Hina et al., 2022), and circular initiatives (Mhatre et al., 2021). Additionally, consumer propensity (Bressanelli et al., 2019) and involvement (De Bruyne and Verleye, 2023; Gomes et al., 2022) in sustainable alternatives, along with the ambiguity in the market demand (Assmann et al., 2023) create a need to adopt new circular solutions. The factor n. 7 *number of TBL, organizational, and institutional drivers and actions* is considered a key factor due to its five links, two from the Business modedl dimension and three from the Circular manufacturing ecosystem dimension. In particular, this factor increases opportunities for the circular business model adoption (Foroozanfar et al., 2022) and promotes its diffusion (Hina et al., 2022). Moreover, this key factor supports the introduction of circular manufacturing practices, such as reverse logistics (Mallick et al., 2023) in the supply chain (Adams et al., 2021), by leveraging specific technology (Jia et al., 2020). The key factor n. 13 *types of circular manufacturing drivers and strategies* has four connections: two with the PLM dimension, one with the Drivers dimension, and one with the Socio-economic aspects dimension. This core factor enhances the sustainable EoL solutions (Kakadellis and Harris, 2020) by enabling different life cycle patterns (Amicarelli et al., 2022). Various circular manufacturing strategies contribute to the introduction of CE practices (Acerbi et al., 2021), while increased environmental awareness among consumers further promotes circular manufacturing strategy adoption (Ada et al., 2023). Lastly, the core factor n. 17 *number of PLM strategies* is connected with five factors: two from the Business model dimension, two from the Socio-economic aspects dimension, and one from the Circular manufacturing dimension. This factor creates opportunities within the organisational model (De Oliveira et al., 2021), but also these PLM strategies play a role in the development of circular PSS (Reim, 2013; Sassanelli et al., 2019b). The factor *numbers of PLM strategies* is influenced by customer voice (Karkasinas and Rentizelas, 2019) and environmental interest (Li et al., 2021a), and it also supports the production of high-quality remanufactured products (Li et al., 2021a). The success factors detected justify the reason for the research and are at the end of the chain. In fact, *level of circular consumption (Gomes et al., 2022)* and *level and propensity of sustainable purchase intention (Abbate et al., 2023; Hugo et al., 2021)*, both from the Socio-economic aspects dimension, explain the customer interest in sustainable solutions. However, these factors could cause a direct RE by an undesired increase in demand. The factor n. 16 *quality of remanufactured products* explains the need to introduce high-quality circular products to prevent economy-wide RE (Li et al., 2021a). The last success factor n. 19 is the *quantity of closed loop life cycle*, which reflects the goal of closing product life cycles. However, this could potentially lead to an indirect RE, as cost reductions may result in increased consumption of other goods (L. Ding et al., 2023). In relation to these success factors, measurable success factors were detected to assess the project from a qualitative and quantitative perspective. For this role, two factors were detected: *numbers of green initiatives* (factor n. 10) and *quality of reverse logistic practice* (factor n. 14). In the last step, these factors were linked together through a cause-effect connection to develop the final reference model (Figure 16). This reference model maps the existing situation concerning the potential occurrence of the RE of CE and illustrates interconnections between the five dimensions of CE-RE, based on the analysis of the literature. The different colours in the links in Figure 16 indicate distinct types of RE: green for direct effect, yellow for indirect effect, orange for economy-wide effect, and blue for transformational effect. For instance, a direct RE may arise from the link between *types of customized innovative and sustainable circular product* (factor n. 18) and the *amount of consumer network* (factor n. 28). In this case, the demand for the same product could increase as customer preferences shift (Conlon, 2020). Similarly, the connection between *level of consumer motivation* (factor n. 26) and the *level of pro-environmental awareness and attitude* (factor n. 5) could lead to a direct RE, as higher motivation encourages the adoption of sustainable solutions (Fogt Jacobsen et al., 2022). An indirect RE may occur when consumer responsibility towards sustainable solutions changes after the introduction of CE practices (Mies and Gold, 2021). Furthermore, the *quality of product usage data* (factor n. 22) could create ambiguity in market demand, potentially driving increased consumption of alternatives products (Meyer et al., 2021), influenced by consumer behaviour (Brandt et al., 2021). Another example of an indirect RE is when customised and innovative sustainable products do not fit the consumer's network, leading to higher consumption of traditional products (Agrawal et al., 2022). An economy-wide RE can emerge when the adoption of various circular manufacturing technologies facilitates the introduction of CE practices, but also causes changes in demand or supply due to increased efficiency (Chen et al., 2022). The reference model developed gives a quick and easy representation of the existing situation within the circular manufacturing and how potential REs occur to understand which dimension of the CE-RE is most involved.

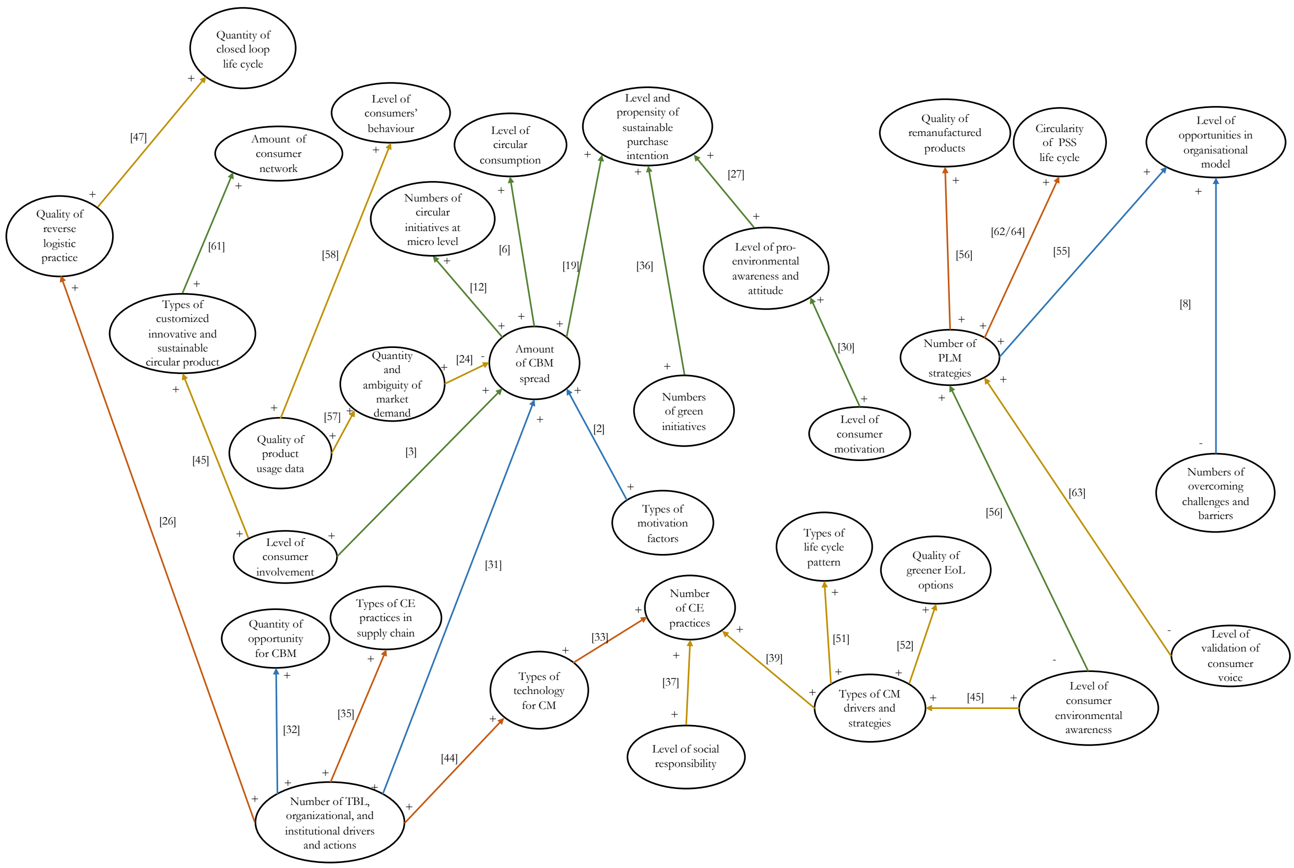


Figure 16. Reference Model (green arrow = direct RE; yellow arrow = indirect RE; orange arrow = economy-wide RE; blue arrow = transformational RE).

4.2.3 From research gaps to industrial perspectives

To deepen the understanding gained from the conceptual maps and the reference model, the next step involved identifying the main research gaps within the field. The systematic literature review was conducted and led to the selection of 65 papers, and the research gaps explicitly highlighted in each contribution were systematically analysed. This process led to the identification of seven key categories of gaps (along with the number of specific gaps associated with each): attitudes and behaviours (14); ecosystem configurations (8); in-depth conceptual studies (4); industrial applications (23); performance measurement (14); policy and regulations (4); and technological potential (21). A brief description of each detected gap, classified by dimension and gap category, is provided in Table 30.

Table 30. Gap classification according to the seven categories identified (D1 = Business Model; D2 = Drivers; D3 = Circular manufacturing ecosystem; D4 = Product Lifecycle Management; D5 = Socio-economic aspects)

Ref.	Specific Gaps and related gap categories	Dimensions (D)				
		D1	D2	D3	D4	D5
(De Bruyne and Verleye, 2023)	Attitude-behaviour in a group of people, like customers and governments	X				

(Gomes et al., 2022)	Consumer behaviour research on some circular business model	X				
(Salvador et al., 2021)	Social aspects and RE of a circular bioeconomy	X				
(Salvador et al., 2020)	Circular business model neglects the social dimension of sustainability	X				
(Bressanelli et al., 2019)	Challenges and consequences of actions among supply chain actors	X				
(Merli et al., 2018)	Social wellbeing impact of CE	X				
(Fogt Jacobsen et al., 2022)	Educate consumers on the environmental effects of plastic packaging waste		X			
(Mies and Gold, 2021)	Insufficient regard for various actors' views and social behaviour		X			
(Acerbi and Taisch, 2020)	Restricted examination of macro-level effects on society		X			
(Hugo et al., 2021)	Consumer behaviour in circular fashion and culture and impact		X			
(Silvério et al., 2023)	Human behaviour in adopting CE practices in firms		X			
(Jia et al., 2020)	Social factors in CE field		X			
(Pålsson and Olsson, 2023)	Factors that influence consumer's choice of ecologically friendly packaging					X
(Valencia et al., 2023)	Evaluation study to assess the general social impacts of the CE					X
	Total: Attitudes and behaviours category (14 gaps, 16% of total)	**6**	**6**	**-**	**-**	**2**
(Eisenreich et al., 2022)	Strategic management frameworks and CE effects in value chain categories	X				
(Sehnem et al., 2022)	Expand CE and innovation research in other circular fields	X				
(Salvador et al., 2022)	General approach of technical quality methods	X				
(Kuzma et al., 2021)	New general categories to achieve sustainable	X				
(Bressanelli et al., 2019)	Study supply chain configuration types to meet CE initiatives	X				
(Despeisse and Acerbi, 2022)	Industrial systems that are eco-friendly and circular		X			
(L. Ding et al., 2023)	Framework for circular logistics integration in the lifecycle			X		
(Jäger-Roschko and Petersen, 2022)	Information sharing between organisations			X		
	Total: Ecosystems configurations category (8 gaps, 9% of total)	**5**	**1**	**2**	**-**	**-**
(Blüher et al., 2020)	Standardised practices to consider the negative impact on sustainability		X			
(Silvério et al., 2023)	Understanding of the CE's effects in different geographical areas		X			
(Reim, 2013)	Study on new PSS business model categories				X	
(Sassanelli et al., 2019b)	More studies to recognise the relationship between lean thinking and PSS				X	
	Total: In-depth conceptual analysis category (4 gaps, 4,5% of total)	**-**	**2**	**-**	**2**	**-**
(Mhatre et al., 2021)	Examine which business models are most effective for which sectors.	X				
(Munaro et al., 2020)	More consolidated theory on business model with CE in construction	X				
(Rosa et al., 2019a)	Actions to practically promote a business model shift in CE practice	X				
(Rosa et al., 2019b)	Benefits and obstacles of CE of WEEE industry	X				

(Merli et al., 2018)	Need for more practical CE implementation cases in companies	X				
(Mallick et al., 2023)	Specific reverse logistics components in industry		X			
(Hugo et al., 2021)	More practical studies on the application of CE in fashion firms		X			
(Assmann et al., 2023)	Examination of how specific industry sectors adopt circular business model		X			
(Abbate et al., 2023)	Sustainability in textile, apparel and fashion is not related to zero waste.		X			
(Tanveer et al., 2023)	Focus only on food industry; lack in research on food contact films (made of different materials)		X			
(Hina et al., 2022)	Lack of empirical evidence		X			
(Chen et al., 2022)	Achieve net-zero emission: manage better resources in construction projects		X			
(Mehmood et al., 2021)	No sector-specific research		X			
(Aloini et al., 2020)	Implement research in other dimensions		X			
(Ada et al., 2023)	Interactions between packaging business and food industry members			X		
(Amicarelli et al., 2022)	Further proof from full LCA studies			X		
(Brandt et al., 2021)	Extend and validate the topic map's use cases, barriers, and drivers				X	
(Corallo et al., 2020)	More results from food industry examination				X	
(Reim, 2013)	Case studies about PSS to meet strategic and operational levels				X	
(Sakao and Nordholm, 2021)	Additional use case analysis				X	
(Conlon, 2020)	Empirical studies in fashion industry on influence of digital world on PLM				X	
(Pålsson and Olsson, 2023)	Further studies on the industry of reusable packaging					X
(Valencia et al., 2023)	More case studies in the built environment, agriculture, and food					X
	Total: Industrial applications category (23 gaps, 26% of total)	**5**	**9**	**2**	**5**	**2**
(Försterling et al., 2023)	Metrics for sustainability performance, and social dimensions	X				
(Kanzari et al., 2022)	Expected financial performance, evaluation parameters, and design.	X				
(van Loon et al., 2021a)	Micro-level for environmental performance; economic and social dimensions not considered	X				
(Vegter et al., 2020)	Implement performance metrics that consider TBL	X				
(Merli et al., 2018)	Provide CE indicators to evaluate the micro level of analysis	X				
(Salvador et al., 2022)	Develop a quantity method to evaluate circularity	X				
(Kuzma et al., 2021)	Generalize results to evaluate sustainable development objectives	X				
(Mallick et al., 2023)	Develop a performance measurement to assess reverse logistic benefits		X			
(Acerbi et al., 2021)	Framework must be operationalized with quantitative analysis		X			
(Metic and Pigosso, 2022)	Lack of reliable methods to assess and predict RE's potential magnitude		X			
(Silvério et al., 2023)	Develop performance measures to assess the CE effects in firms		X			
(Marić et al., 2023)	Integrating with quantitative and qualitative studies			X		
(Liu et al., 2023)	Additional metrics to track sustainable supply chain activity			X		

(Karkasinas and Rentizelas, 2019)	Conduct quantitative analysis along the manufacturing process				X	
Total: Performance measurements category (14 gaps, 16% of total)		**7**	**4**	**2**	**1**	**-**
(Chauhan et al., 2022)	Examine the political barriers	X				
[47]	Implications of policy on circular business model adoption		X			
(Silvério et al., 2023)	Examine the policy actions to encourage the adoption of CE		X			
(Silvestri et al., 2021)	Political initiatives to assist businesses in using green technologies		X			
Total: Policy and regulations category (4 gaps, 4,5% of total)		**1**	**3**	**-**	**-**	**-**
(Chauhan et al., 2022)	Investigate the links between CE and digitalization	X				
(S. Ding et al., 2023)	Insufficient knowledge of internet of things' environmental benefits	X				
(Abideen et al., 2021)	Additional research on reverse logistics and augmented reality	X				
(Cioffi et al., 2020)	Digital technology for system simulation/scheduling/control/optimisation	X				
(Acerbi et al., 2021)	Digital technologies to assess the impact of data and to track and manage it		X			
(Adams et al., 2021)	Digitalization and CE to promote sustainability in the food supply chain		X			
(Silvério et al., 2023)	Analyse how industry 4.0 promotes CE practices		X			
(Jia et al., 2020)	Investigate the technological effects of applying CE practices.		X			
(Jäger-Roschko and Petersen, 2022)	Investigate the benefits of CE achievable with information sharing			X		
(Sood et al., 2022)	Drive for artificial intelligence adoption; supply chain and traditional additive manufacturing restructured			X		
(Kerdlap et al., 2019)	Reduce the size of waste sorting plants and food waste digesters; enhance cooperative platforms for IS			X		
(Liu et al., 2023)	Algorithms to turn data into information; digitalization of sustainable supply chains			X		
(Barrios et al., 2022)	Investigate the connection between the PLM and internet of things platforms				X	
(De Oliveira et al., 2021)	Framework for the digital transformation and sustainability transition				X	
(Li et al., 2021a)	Integrated system with multiple product lifecycles for remanufacturing				X	
(Meyer et al., 2021)	Data analytics to integrate conventional design processes for small medium enterprises				X	
(Sassanelli et al., 2019b)	Examine the digital technologies to manage the lean PSS lifetime				X	
(Sakao and Nordholm, 2021)	Analysis of big data analytics and the internet of things to support the PLM system				X	
(Conlon, 2020)	Study about how changes in the developing digital world influence PLM				X	
(Agrawal et al., 2022)	More research on industry 4.0 integration with CE and circular manufacturing					X
(Kumar et al., 2022)	Technology for quality and safety concerns in sustainable food supply chain					X
Total: Technologies potential category (21 gaps, 24% of total)		**4**	**4**	**4**	**7**	**2**
Overall occurrence of gaps in CE-RE dimensions (88 gaps, 100%)		**28**	**29**	**10**	**15**	**6**

Attitudes and behaviours of consumers and supply chain actors play a central role in generating RE related to CE strategies. In the Business model dimension, the interest in consumer actions is emphasized (Gomes et al., 2022), raising in particular the need of focus on the social aspect of sustainability (Salvador et al., 2020). Also the impact on social wellbeing as well as on the different supply chain actors involved within the implementation of CE strategies require further investigation (Merli et al., 2018), (Bressanelli et al., 2019). More research is required to investigate the possibility that a consumer group's attitudes contribute to RE (De Bruyne and Verleye, 2023; Salvador et al., 2021). Within drivers dimension, it has been highlighted that the social factors need more consideration for a successful implementation of CE (Jia et al., 2020; Mies and Gold, 2021), and that, in this context, human behaviour during the adoption of CE practices should be examined (Acerbi and Taisch, 2020; Silvério et al., 2023), also educating consumers to take positive actions (Fogt Jacobsen et al., 2022), such as their behaviour in circular fashion and culture (Hugo et al., 2021). In the socio-economic aspects dimension, the factors influencing consumers' ecological choices must be examined by assessing their impact (Pålsson and Olsson, 2023; Valencia et al., 2023).

Ecosystem configurations category refer to the interaction dynamics of the actors involved in achieving sustainability. Supply chain configurations, such as the use of reverse logistics (Circular manufacturing ecosystem dimension) (L. Ding et al., 2023), need investigation to evaluate the CE effects on the value chain (Bressanelli et al., 2019; Eisenreich et al., 2022). This category raises the need of fostering information sharing (Circular manufacturing ecosystem dimension) (Jäger-Roschko and Petersen, 2022) inside eco-friendly industrial systems (Drivers dimension) (Despeisse and Acerbi, 2022) to enact innovative circular strategies (Business model dimension) (Sehnem et al., 2022). To achieve the sustainability of the whole ecosystem, an overall approach should be developed, with general approaches of technical quality methods (Kuzma et al., 2021; Salvador et al., 2022).

In-depth conceptual studies category highlights the need of more in-depth theoretical studies. In the PLM dimension, PSSs should be investigated more to manage the lifecycle of a product (Reim, 2013) and to connect them with lean thinking (Sassanelli et al., 2019b). In the drivers dimension, CE's effects in different geographical areas should be deepened (Silvério et al., 2023). In addition, further studies should consider the negative impact caused by standard practices (Blüher et al., 2020).

To the category of industrial applications is related to the need of practical cases in firms or of more studies in the same or different industries different from the examined research. In PLM dimension, case studies would be necessary to adopt PSS for operational levels and validate them in strategic approaches (Reim, 2013) and analyse possible barriers and drivers (Brandt et al., 2021; Sakao and Nordholm, 2021). As for the drivers' dimension, empirical evidences to enable the correct implementation and application of CE in companies are needed (Hina et al., 2022; Hugo et al., 2021). Circular business models require practical case studies to investigate their successful and proper implementation (Merli et al., 2018). In construction sector, more studies would be needed on how circular business models operate (Munaro et al., 2020) to optimize resource use and achieve net-zero emissions (Chen et al., 2022). In fashion and textile industries, empirical studies are needed to investigate how PLM is influenced by digital technologies (Conlon, 2020) to minimize waste (Abbate et al., 2023). The food industry should be concerned about the interrelationships with reusable packaging (Ada et al., 2023; Pålsson and Olsson, 2023) and the materials from which food contact films are made (Tanveer et al., 2023) throughout the entire product lifecycle (Corallo et al., 2020). Several gaps refer to examining the circular business model (Mhatre et al., 2021) proposed in other sectors to find the most suitable for the application of this kind of business model (Assmann et al., 2023) and maximize the circular benefits (Rosa et al., 2019b). In some studies, CE practices didn't include action (Rosa et al., 2019a) for a specific industrial sector (Mehmood et al., 2021), making necessary more research (Aloini et al., 2020) and assessment in other fields (Amicarelli et al., 2022) such as built environment and agriculture (Valencia et al., 2023). Finally, some studies should consider specific reverse logistic components in industry (Mallick et al., 2023).

The category of performance measurements generally highlights the lack of a system to evaluate CE and RE. In particular, a lack of metrics for environmental, economic, and social performance is highlighted in many sources (Försterling et al., 2023; van Loon et al., 2021a; Vegter et al., 2020). Moreover, further studies should develop a quantitative and qualitative method to assess circular strategies and reach sustainable objectives (Kuzma et al., 2021; Marić et al., 2023; Salvador et al., 2022). Operational CE indicators need to be developed in firms for evaluating manufacturing processes (Acerbi et al., 2021; Karkasinas and Rentizelas, 2019; Merli et al., 2018; Silvério et al., 2023). Other performance metrics should evaluate the sustainability of the value chain, focusing on supply chain (Liu et al., 2023) and reverse logistics (Mallick et al., 2023). Lastly, methods to assess and predict the RE of CE would be required for the proper selection and design of circular strategies (Kanzari et al., 2022; Metic and Pigosso, 2022).

In policy and regulations, gaps focus on political initiatives for the CE. The category consists of political barriers that hamper CE initiatives (Chauhan et al., 2022; Silvestri et al., 2021) and policy actions that encourage the adoption of CE strategies (e.g., circular business model) (Assmann et al., 2023; Silvério et al., 2023).

The category of technologies potential relates to the examination of the use of technologies to promote CE. It is confirmed that Industry 4.0 is one of the main enablers for CE. Different gaps underline the relevance of investigating how to integrate industry 4.0 technologies and CE strategies (Agrawal et al., 2022; Silvério et al., 2023). For example, the Internet of Things could lead to environmental benefits (S. Ding et al., 2023) and support PLM systems (Barrios et al., 2022; Sakao and Nordholm, 2021). Data analytics could help design a successful circular process (Meyer et al., 2021), and the adoption of artificial intelligence and additive manufacturing could modify the traditional supply chain (Sood et al., 2022). The supply chain needs the support of technologies to manage and monitor the level of sustainability (Kumar et al., 2022; Liu et al., 2023), especially in the food industry (Adams et al., 2021), and increase efficient reverse logistics (Abideen et al., 2021). More studies should concern the digital transformation to achieve sustainability transition (De Oliveira et al., 2021) and connecting to CE for sharing information to obtain more benefits (Chauhan et al., 2022; Jäger-Roschko and Petersen, 2022). Digital technologies in manufacturing should be a system to manage, schedule, and control (Cioffi et al., 2020) the effects of CE practices (Acerbi et al., 2021; Jia et al., 2020). In addition, the digital world influences and supports PLM systems (Conlon, 2020; Li et al., 2021a), and it should be studied how to manage the lean PSS lifetime (Sassanelli et al., 2019b). Finally, technologies should be studied for practical application in waste sorting plants and industrial symbiosis (IS) (Kerdlap et al., 2019).

Finally, gap categories were prioritized, indicating Industrial applications, Technologies potential and Performance measurements as those calling more for further research, followed by Attitudes and behaviours, Ecosystems configurations, In-depth conceptual analysis, and Policy and regulations.

To investigate the industrial perspective—one of the main gaps previously identified—a series of semi-structured interviews was conducted. The interviews revealed that Companies A and B have already adopted circular strategies within their processes, whereas Company C has not yet implemented any CE-related initiatives.

Company A was developing new technologies aimed at fully recovering components from their products. Company B focuses on material recycling and currently incorporates 25% post-consumer plastics into their production. Although Company C has not adopted circular strategies, it still aims to minimise raw material usage through repair activities and product dismantling.

The benefits obtained through these approaches differ across companies. Company A anticipates future regulations and brings compliant solutions to the market, monitoring progress through LCA-based key performance indicators (KPIs). Company B seeks to increase the proportion of closed-loop plastics in its vehicles through both mechanical and chemical recycling, assessing progress with a dedicated KPI measuring the percentage of recycled plastic relative to total plastic used. Company C, despite not implementing CE strategies, has introduced an internal sustainability KPI to certify its CO_2 neutrality.

Only Companies A and B reported negative effects associated with implementing circular strategies. Company A highlighted additional costs linked to the new technologies required for extra functions such as disassembly. Company B reported challenges in validating recycled materials and noted the increased burden of technical and feasibility testing.

Although none of the companies was familiar with the concept of REs of the CE, all recognised the presence of unintended negative consequences arising from the implementation of circular strategies.

4.3 Results from Stage 3: Prescriptive Study

This section presents the results obtained in the third stage of the DRM—the *Prescriptive Study*—which focuses on developing the impact model and then the tool.

4.3.1 Detailing the reference model factors for developing the impact model

The first activity in this stage consisted of detailing the factors of the CE-RE reference model by identifying and integrating the RE mechanisms into the model. Building on the conceptual maps and the reference model developed in the previous stages, this step aimed to categorise the factors according to the rebound mechanisms that characterise their interconnections. To do so, the RE mechanisms defined from the consumer and producer perspectives proposed by (Guzzo et al., 2024) were taken as a basis. Each link across the factors and dimensions in the CE-RE reference model was analysed to determine which RE mechanism it most closely corresponds to. Through this analysis, 17 RE mechanisms were unveiled across different links. Table 31 summarised the relevant factors that contribute to the RE mechanism, categorising them into 13 causes and 19 effects, 13 from a consumer perspective and 19 from a producer perspective.

Table 31. Analysis of the selected factors from the CE-RE reference model and relative RE mechanisms (Cons = Consumer; Prod = Producer; C = Cause; E = Effect)

Dim	Factors	RE mechanisms	Cons	Prod	C	E
Business model	Amount of circular business model spread	Market price		X	X	
	Level of opportunities in organisational model	Labour income		X		X
	Quantity of opportunity for circular business model	Income	X			X
	Circularity of PSS life cycle	Producer-induced demand adjustment		X	X	
		Total	**1**	**3**	**2**	**2**
Drivers	Level of pro-environmental awareness and attitude	Demand adjustment initiated by sufficiency		X	X	
	Number of CE practices	Demand adjustment initiated by efficiency		X	X	
	Number of TBL, organizational, and institutional drivers and actions	Cost-dependent output		X	X	
	Types of motivation factors	Motivational consumption	X			X
	Numbers of overcoming challenges and barriers	New economic activity		X	X	
	Numbers of green initiatives	Output		X	X	
	Types of circular initiatives at micro level	Re-investment		X		X
		Total	**1**	**6**	**5**	**2**
Circular manufacturing ecosystem	Types of CE practices in supply chain	Supply adjustment		X		X
	Types of circular manufacturing drivers and strategies	Re-investment		X		X
	Quality of reverse logistic practice	Factor substitution		X	X	
	Types of technology for circular manufacturing	Cost-dependent output		X		X
	Quality of remanufactured products	Demand adjustment initiated by efficiency		X	X	
		Total	**0**	**5**	**2**	**3**
PLM	Number of PLM strategies	Output		X	X	
	Types of customized innovative and sustainable circular product	Production time		X	X	
	Quantity of closed loop life cycle	Producer-induced demand adjustment		X	X	
	Types of life cycle pattern	Consumption time		X		X
	Quality of greener EoL options	Factor substitution		X	X	
	Quality of product usage data	Re-investment		X		X
		Total	**0**	**6**	**4**	**2**
Socio-economic aspects	Level of consumer involvement	Motivational consumption	X			X
	Level of circular consumption	Market price	X			X
	Level and propensity of sustainable purchase intention	Demand adjustment initiated by sufficiency	X			X
	Level of consumer motivation	Motivational consumption	X			X
	Level of consumer environmental awareness	Motivational substitution	X			X
	Amount of consumer network	Consumption time	X			X
	Quantity and ambiguity of market demand	Motivational consumption	X			X
	Level of social responsibility	Motivational substitution	X			X
	Level of consumers' behaviour	Re-spending	X			X
	Level of validation of consumer voice	Motivational consumption	X			X
		Total	**10**	**0**	**0**	**10**
		TOTAL	**13**	**19**	**13**	**19**

In detail, the consumption time mechanism refers to efficiency actions that reduce the time required to consume a product, leading to increased resource consumption from a consumer perspective. This effect is evident in the factor *types of life cycle pattern* (PLM dimension) (Amicarelli et al., 2022) and *amount of consumer network* (Socio-economic aspects dimension) (Conlon, 2020). The cost-dependent output mechanism indicates that efficiency improvements in production are accompanied by enhancements involving different production factors. This was identified in the link between the cause *number of TBL, organizational, and institutional drivers and actions* (Driver dimension) and the effect *types of technology for circular manufacturing* (Circular manufacturing ecosystem dimension) (Jia et al., 2020). The demand adjustment initiated by efficiency occurs when efficiency improvements reduce resource use, but the resulting lower prices may increase overall resource consumption. This was identified as a cause in two factors: *number of CE practices* (Driver dimension) (Chen et al., 2022), and *quality of remanufactured products* (Circular manufacturing ecosystem dimension) (Li et al., 2021a). The demand adjustment initiated by sufficiency considers sufficiency as a strategy that can be offset by increased demand from another producer. This was observed in the link between the cause *level of pro-environmental awareness and attitude* (Driver dimension) and the effect *level and propensity of sustainable purchase intention* (Socio-economic aspects dimension) (Abbate et al., 2023). The factor substitution mechanism describes how lower costs can increase demand for other, more resource-intensive products. This was identified in the *quality of reverse logistic practice* (Circular manufacturing ecosystem) (L. Ding et al., 2023) and *quality of greener EoL options* (PLM dimension) (Kakadellis and Harris, 2020), both acting as causes of this mechanism. The income mechanism refers to efficiency actions that enhance product efficiency and decrease consumption costs, which, in turn, generate additional demand. This effect was evident in the factor *quantity of opportunity for circular business model* (Business model dimension) (Foroozanfar et al., 2022). The labour income mechanism describes how efficiency in production reduces costs but may lead to higher wages for workers. This was observed in the effect *level of opportunities in organisational model* (Business model dimension) (De Oliveira et al., 2021). The market price mechanism refers to cost reductions that lower prices, encouraging consumers to re-spend and reinvest, generating additional demand effects. This was detected in the link between the cause *amount of circular business model spread* (Business model dimension) and the effect *level of circular consumption* (Socio-economic dimension) (Gomes et al., 2022). The motivational consumption mechanism involves consumer responses to efficiency improvements, as observed in the following effect factors from the Socio-economic aspects dimension: *types of motivation factors* (Driver dimension) (Försterling et al., 2023)*, level of consumer involvement* (De Bruyne and Verleye, 2023)*, level of consumer motivation* (Fogt Jacobsen et al., 2022)*, quantity and ambiguity of market demand* (Meyer et al., 2021)*,* and *level of validation of consumer voice* (Karkasinas and Rentizelas, 2019) all from the Socio-economic aspects dimension. The motivational substitution mechanism describes consumer responses to secondary goods products, as seen in the effect factors *level of consumer environmental awareness* (Li et al., 2021a) and *level of social responsibility* (Mies and Gold, 2021) (Socio-economic aspects dimension). The new economic activity refers to societal efficiency improvements that lead to increased consumption. This was identified as a cause in the factor *numbers of overcoming challenges and barriers* (Driver dimension) (Salvador et al., 2022). The output mechanism describes how lower production costs lead to an improved supply of the same products. This was observed in two cause factors: *numbers of green initiatives* (Driver dimension) (Hugo et al., 2021), and *number of PLM strategies* (PLM dimension) (Karkasinas and Rentizelas, 2019). The producer-induced demand adjustment occurs when efficiency improvements in one process reduce demand for a product but may increase demand for additional products. This was identified in the cause factors: *quantity of closed loop life cycle* (PLM dimension) (L. Ding et al., 2023), and *circularity of PSS life cycle* (Business model dimension) (Reim, 2013; Sassanelli et al., 2019b). The production time mechanism considers efficiency in production that enhances production rates. This was observed in the cause factor *types of customized innovative and sustainable circular product* (PLM dimension) (Conlon, 2020). The re-investment mechanism occurs when lower production costs lead to increased supply of other products. This was detected in the following effect factors: *quality of product usage data* (PLM dimension) (Brandt et al., 2021), *types of circular manufacturing drivers and strategies* (Circular manufacturing ecosystem dimension) (Ada et al., 2023), and *types of circular initiatives at micro level* (Driver dimension) (Mhatre et al., 2021). The re-spending mechanism refers to situations where saved budgets are redirected to other potentially pollutant activities. This was mentioned as an effect factor *level of consumers' behaviour* (Socio-economic aspects dimension) (Brandt et al., 2021).The supply adjustment mechanism describes how a sufficiency strategy adopted by one supplier can be offset by an increase in supply from another supplier. This was detected in the link between the cause *number of TBL, organizational, and institutional drivers and actions* (Driver dimension) and the effect *types of CE practices in supply chain* (Circular manufacturing ecosystem dimension) (Adams et al., 2021).

Building upon the previous activity, the subsequent step focused on identifying and categorising the links of the CE-RE reference model according to the four classes of the circular manufacturing data model (i.e., product, process, management, and technology). This step was essential to determine which types of data should be collected in a CE-RE context and to support the detection of RE within manufacturing settings. This work aims to pair the links of the CE-RE reference model (i.e., an evolution of CE-RE conceptual maps) with the circular manufacturing data model. The outcome is a categorisation of the links between two factors from different dimensions of the CE-RE reference model (i.e., business model, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects) into the four categories of classes of the circular manufacturing data model (i.e., product, process, management, and technology) (Acerbi et al., 2022), as illustrated in Table 32. It turns out that five links of factors of the CE-RE reference model are associated to the product category of the circular manufacturing data model, eight to the process category, twelve to the management category, and eight to the technology category. This categorisation supports identifying the relevant data that should be collected in the CE-RE context and provides valuable insights for identifying the occurrence of RE within a manufacturing company in the different dimensions of CE-RE. However, this step also highlighted that data availability may represent a significant constraint in practical applications. While the circular manufacturing data model specifies the types of information required, many companies may not systematically collect, structure, or integrate such data across systems (e.g., PLM). As a result, several links of the CE-RE reference model, particularly those associated with behavioural aspects, ecosystem interactions, and socio-economic factors, may be difficult to operationalise due to the lack of accessible, consistent, or standardised datasets. Acknowledging these limitations is crucial for understanding how data gaps could hamper RE detection and underlines the need for future research on improving data interoperability, enhancing CE-oriented data architectures, and developing dedicated data collection protocols tailored to circular manufacturing.

Table 32. Analysis of the links and the related circular manufacturing data model category (D1 = Business Model; D2 = Drivers; D3 = Circular manufacturing ecosystem; D4 = Product Lifecycle Management; D5 = Socio-economic aspects)

Data category	Factor of origin	Dimension D1	D2	D3	D4	D5	Factor of destination	Dimension D1	D2	D3	D4	D5	Ref.
Product	Level of consumer motivation					X	Level of pro-environmental awareness and attitude		X				(Fogt Jacobsen et al., 2022)
	Types of circular manufacturing drivers and strategies			X			Quality of greener EoL options				X		(Kakadellis and Harris, 2020)
	Quality of product usage data				X		Quantity and ambiguity of market demand					X	(Meyer et al., 2021)
	Types of customized innovative and sustainable circular product				X		Amount of consumer network					X	(Conlon, 2020)
	Level of consumer involvement					X	Types of customized innovative and sustainable circular product				X		(Agrawal et al., 2022)
	Total	**0**	**0**	**1**	**2**	**2**		**0**	**1**	**0**	**2**	**2**	**5**
Process	Quality of reverse logistic practice			X			Quantity of closed loop life cycle				X		(L. Ding et al., 2023)
	Number of PLM strategies				X		Quality of remanufactured products			X			(Li et al., 2021b)
	Level of validation of consumer voice					X	Number of PLM strategies				X		(Karkasinas and Rentizelas, 2019)
	Number of TBL, organizational, and institutional drivers and actions		X				Types of CE practices in supply chain			X			(Adams et al., 2021)
	Number of TBL, organizational, and institutional drivers and actions		X				Types of technology for circular manufacturing			X			(Jia et al., 2020)
	Level of consumer environmental awareness					X	Types of circular manufacturing drivers and strategies			X			(Ada et al., 2023)
	Types of circular manufacturing drivers and strategies			X			Types of life cycle pattern				X		(Amicarelli et al., 2022)
	Types of circular manufacturing drivers and strategies			X			Number of CE practices		X				(Acerbi et al., 2021)
	Total	**0**	**2**	**3**	**1**	**2**		**0**	**1**	**4**	**3**	**0**	**8**
Management	Amount of circular business model spread	X					Level and propensity of sustainable purchase intention					X	(Bressanelli et al., 2019)
	Level of pro-environmental awareness and attitude		X				Level and propensity of sustainable purchase intention					X	(Abbate et al., 2023)
	Numbers of green initiatives		X				Level and propensity of sustainable purchase intention					X	(Hugo et al., 2021)
	Level of consumer involvement					X	Amount of circular business model spread	X					(De Bruyne and Verleye, 2023)
	Amount of circular business model spread	X					Level of circular consumption					X	(Gomes et al., 2022)
	Amount of circular business model spread	X					Numbers of circular initiatives at micro level		X				(Mhatre et al., 2021)
	Types of motivation factors		X				Amount of circular business model spread	X					(Försterling et al., 2023)
	Level of social responsibility					X	Number of CE practices		X				(Mies and Gold, 2021)
	Number of TBL, organizational, and		X				Amount of circular business model spread	X					(Hina et al., 2022)

	institutional drivers and actions												
	Numbers of overcoming challenges and barriers		X				Level of opportunities in organisational model	X					(Salvador et al., 2022)
	Quantity and ambiguity of market demand					X	Amount of circular business model spread	X					(Assmann et al., 2023)
	Number of TBL, organizational, and institutional drivers and actions		X				Quantity of opportunity for circular business model	X					(Foroozanfar et al., 2022)
	Total	**3**	**6**	**0**	**0**	**3**		**6**	**2**	**0**	**0**	**4**	**12**
Technology	Number of PLM strategies				X		Quality of remanufactured products			X			(Li et al., 2021b)
	Quality of product usage data				X		Quantity and ambiguity of market demand					X	(Brandt et al., 2021)
	Level of consumer involvement					X	Types of customized innovative and sustainable circular product				X		(Agrawal et al., 2022)
	Types of technology for circular manufacturing			X			Number of CE practices		X				(Chen et al., 2022)
	Number of PLM strategies				X		Circularity of PSS life cycle	X					(Reim, 2013; Sassanelli et al., 2019b)
	Number of PLM strategies				X		Level of opportunities in organisational model	X					(De Oliveira et al., 2021)
	Quality of reverse logistic practice			X			Quantity of closed loop life cycle				X		(L. Ding et al., 2023)
	Types of customized innovative and sustainable circular product				X		Amount of consumer network					X	(Conlon, 2020)
	Total	**0**	**0**	**2**	**5**	**1**		**2**	**1**	**1**	**2**	**2**	**8**
	TOTAL	**3**	**8**	**6**	**8**	**8**		**8**	**5**	**5**	**7**	**8**	**33**

The product category refers to items manufactured by a company to satisfy end-users needs while adhering to CE pillars. In this category, five links were detected. The factor *Level of consumer motivation* (Socio-economic aspects dimension) is linked to *Level of pro-environmental awareness and attitude* (Drivers dimension), highlighting the interest in producing sustainable product using sustainable components to meet the consumer needs. potentially leading to higher product consumption (Fogt Jacobsen et al., 2022). The link between *Types of circular manufacturing drivers and strategies* (Circular manufacturing ecosystem dimension) and *Quality of greener EoL options* (PLM dimension) emphasizes the importance of high-quality product components in achieving sustainable EoL solutions. However, this could inadvertently reduce product longevity due to the availability of sustainable disposal options (Kakadellis and Harris, 2020). The link between *Quality of product usage data* (PLM dimension) and *Quantity and ambiguity of market demand* (Socio-economic aspects dimension) illustrates the necessity of using data collected from used products to guide the production of new items. This link may lead to an increase in to meet consumer demand (Meyer et al., 2021). The link between *Types of customized innovative and sustainable circular product* (PLM dimension) and *Amount of consumer network* (Socio-economic aspects dimension) reflects the role of product customization in meeting the consumer request during new product development, potentially resulting in increased production (Conlon, 2020). The last link between *Level of consumer involvement* (Socio-economic aspects dimension) and *Types of customized innovative and sustainable circular product* (PLM dimension) highlights the necessity of developing new products that incorporate consumer needs and sustainable intentions. However, this could also contribute to increased consumption (Agrawal et al., 2022).

The process category encompasses actions adopted during production to implement circular strategies. Eight links were identified in this second category. The link between *Quality of reverse logistic practice* (Circular manufacturing ecosystem dimension) and *Quantity of closed loop life cycle* (PLM dimension) supports product reintegration into the close loop, but this may lead to increased production (L. Ding et al., 2023). The factor *Number of PLM strategies* (PLM dimension) is linked to *Quality of remanufactured products* (Circular manufacturing ecosystem dimension), emphasizing the role of PLM solutions in remanufacturing products to their original quality, though this may result in imperfect substitution compared to new products (Li et al., 2021b). The link between *Level of validation of consumer voice* (Socio-economic aspects dimension) and *Number of PLM strategies* (PLM dimension) underlines the importance of considering consumer interests during production and development, potentially leading to increase production (Karkasinas and Rentizelas, 2019). The link between *Number of TBL, organizational, and institutional drivers and actions* (Drivers dimension) and *Types of CE practices in supply chain* (Circular manufacturing ecosystem dimension) underscores the need for circular solutions in the supply chain as a response to new regulations, possibly triggering systemic changes across the market (Adams et al., 2021). The factor *Number of TBL, organizational, and institutional drivers and actions* (Drivers dimension) is linked to *Types of technology for circular manufacturing* (Circular manufacturing ecosystem dimension), demonstrating the necessity of modifying traditional linear processes by integrating circular manufacturing strategies to comply with new regulations. However, this may also lead to shifts in both demand and supply (Jia et al., 2020). The link between *Level of consumer environmental awareness* (Socio-economic aspects dimension) and *Types of circular manufacturing drivers and strategies* (Circular manufacturing ecosystem dimension) reflects consumers' preference for companies adopting circular strategies, though this may also contribute to increased production (Ada et al., 2023). In addition, the factor *Types of circular manufacturing drivers and strategies* (Circular manufacturing ecosystem dimension) is linked to both *types of life cycle pattern* (PLM dimension) (Amicarelli et al., 2022) and *Number of CE practices* (Driver dimension) (Acerbi et al., 2021), illustrating the shift towards circular solutions in the product lifecycle and CE strategies adoption, ultimately resulting in increases in both production and consumption.

The management category involves activities related to planning, organizing, directing, and controlling business operations to achieve objectives. This is the most populated category, with twelve links. The factor *Amount of circular business model spread* (Business model dimension) is linked to *Level and propensity of sustainable purchase intention* (Socio-economic aspects dimension), reflecting how circular business model adoption aligns with the consumer demand for sustainable products, though it may lead to increased consumption (Bressanelli et al., 2019). The link between *Level of pro-environmental awareness and attitude* (Drivers dimension) and *Level and propensity of sustainable purchase intention* (Socio-economic aspects dimension) highlights the necessity of CE strategies to satisfy the consumer expectations. However, satisfying these needs could result in increased production (Abbate et al., 2023). Similarly, the link between *Numbers of green initiatives* (Drivers dimension) and *Level and propensity of sustainable purchase intention* (Socio-economic aspects dimension) reinforces the need for circular solutions to fulfil consumer requests, which may also lead to higher production (Hugo et al., 2021). The link between *Level of consumer involvement* (Socio-economic aspects dimension) and *Amount of circular business model spread* (Business model dimension) stresses the necessity of circular business model adoption to engage consumer needs, potentially increasing production to satisfy demand (De Bruyne and Verleye, 2023). The factor *Amount of circular business model spread* (Business model dimension) is linked to *Level of circular consumption* (Socio-economic aspects dimension), showing how the circular business model adoption influences the consumption, potentially leading to increased consumption (Gomes et al., 2022). In addition, its link to *Numbers of circular initiatives at micro level* (Drivers dimension) (Mhatre et al., 2021) underscores how circular business model adoption facilitates the introduction of circular strategies, potentially leading to broader market transformation. The link between *Types of motivation factors* (Drivers dimension) and *Amount of circular business model spread* (Business model dimension) explains the role of motivational factors in the adoption of circular business model, possibly resulting in increased both production and consumption (Försterling et al., 2023). The link between *Level of social responsibility* (Socio-economic aspects dimension) and *Number of CE practices* (Drivers dimension) reveals how the CE initiatives spread through interactions with other actors, driving market-wide change (Mies and Gold, 2021). The link between *Number of TBL, organizational, and institutional drivers and actions* (Drivers dimension) and *Amount of circular business model spread* (Business model dimension) shows how policies and regulations promote the adoption of circular business model, potentially causing shifts in the economy and society (Hina et al., 2022). Similarly, the link between *Number of TBL, organizational, and institutional drivers and actions* (Drivers dimension) and *Quantity of opportunity for circular business model* (Business model dimension) reflects this influence, which may lead to systemic changes across the market (Foroozanfar et al., 2022).The link between *Numbers of overcoming challenges and barriers* (Drivers dimension) and *Level of opportunities in organisational model* (Business model dimension) highlights the circular initiatives as solutions to emerging challenges and barriers, though they may also generate unintended negative effects (Salvador et al., 2022). The final link in this category, between *Quantity and ambiguity of market demand* (Socio-economic aspects dimension) and *Amount of circular business model spread* (Business model dimension), illustrates the need for circular business model to monitor and manage market uncertainties, which could result in increased production (Assmann et al., 2023).

The last category is the technology one. This category includes the technologies and the tools that support the transition towards CE in manufacturing. In this category, eight links were detected. The factor *Number of PLM strategies* (PLM dimension) is linked to *Quality of remanufactured products* (Circular manufacturing ecosystem dimension), highlighting the role of sustainable technologies during the adoption of circular strategies, though this may lead to substitution issues with new products (Li et al., 2021b). In addition, the factor *Number of PLM strategies* (PLM dimension) is linked both to *Circularity of PSS life cycle* (Business model dimension) (Reim, 2013; Sassanelli et al., 2019b) and *Level of opportunities in organisational model* (Business model dimension) (De Oliveira et al., 2021), emphasizing the need for an information system to support circular solutions, potentially driving shifts across the entire market. The link between *Quality of product usage data* (PLM dimension) and *Quantity and ambiguity of market demand* (Socio-economic aspects dimension) underscores the importance of tracking product data to align consumer needs. However, this may result in increased production (Brandt et al., 2021). The link between *Level of consumer involvement* (Socio-economic aspects dimension) and *Types of customized innovative and sustainable circular product* (PLM dimension) reflects the role of industry 4.0 technologies in product customization, potentially leading to increased production (Agrawal et al., 2022). The link between *Types of technology for circular manufacturing* (Circular manufacturing ecosystem dimension) and *Number of CE practices* (Drivers dimension) demonstrates the role of technology in successfully implementing circular strategies. However, this may also lead to increased production due to improved efficiency (Chen et al., 2022). The factor *Quality of reverse logistic practice* (Circular manufacturing ecosystem dimension) linked to *Quantity of closed loop life cycle* (PLM dimension) highlights the different tools that support circular activities, though these may also contribute to increased production (L. Ding et al., 2023). The last link, between *Types of customized innovative and sustainable circular product* (PLM dimension) and *Amount of consumer network* (Socio-economic aspects dimension), underscores the potential of information systems in expanding consumer networks, which could lead to higher consumption (Conlon, 2020). This categorisation provides an overview of how links between factors are organized in the data model categories. It also illustrates their role during the adoption of CE strategies to achieve benefits while carefully considering the potential RE that could arise.

These two results formed the foundation for developing the impact model. Specifically, the first step in constructing the impact model involved refining the reference model by narrowing its scope to the factors most closely connected to consumer-related dynamics or external influences, as highlighted through the analysis of links between factors and corresponding RE mechanisms. The factors selected from the reference model, based on their relevance to these mechanisms, are reported in the following table.

The resulting impact model represents the desired situation: a structured framework that enables the detection and identification of where and how REs may occur during the implementation of CE strategies in manufacturing. This model thus provides a forward-looking view of the system, supporting practitioners in anticipating potential unintended consequences while planning CE initiatives.

In the Table 33, the selected factors are identified based on two main criteria—both discussed earlier—namely their ability to explain how REs occur and the feasibility of gathering data on these factors and their interconnections. Following this logic, factors considered external or insufficiently connected to measurable internal processes were excluded. For example, many factors from the Business Model dimension were removed because their role in reflecting the adoption of circular business models within a company is largely mediated by external organisational conditions rather than by operational or behavioural dynamics that can be directly observed and measured. A similar rationale applies to the Driver dimension, where several factors mainly capture external challenges and barriers—such as institutional regulations or general environmental attitudes and awareness—that, while important, do not provide actionable or company-specific data for detecting REs. While all factors within the Circular manufacturing ecosystem and PLM dimensions were retained in the impact model—

given their direct relevance to the adoption of circular strategies in manufacturing and their central role across the product lifecycle—the Socio-economic aspects dimension required a more selective approach. Only a subset of factors was included, specifically those capturing consumer behaviour, which was considered an internal driver capable of triggering REs. These behavioural factors influence demand patterns and may ultimately lead to increased production and resource use, making them essential for understanding how REs materialise during CE implementation.

Table 33. List of factors included in the impact model

Dim.	Reference Model factors	Impact Model factors	Type of factors
Business model	Amount of circular business model spread	Amount of circular business model spread	Key factors
	Level of opportunities in organizational model	-	
	Quantity of opportunity for circular business model	-	
	Circularity of PSS life cycle	Circularity of PSS life cycle	
Drivers	Level of pro-environmental awareness and attitude	-	
	Number of CE practices	Number of CE practices	
	Number of organizational, economic, environmental, social, and institutional drivers and actions	-	Key factors
	Types of motivation factors	-	
	Numbers of overcoming challenges and barriers	-	
	Quantity of green initiatives	-	Measurable Success Factors
	Types of circular initiatives at micro level	Numbers of circular initiatives at micro level	
Circular manufacturing ecosystem	CE practices in supply chain	CE practices in supply chain	
	Types of circular manufacturing drivers and strategies	Types of circular manufacturing drivers and strategies	Key factors
	Types of reverse logistic practice	Types of reverse logistic practice	Measurable Success Factors
	Types of technology for circular manufacturing	Types of technology for circular manufacturing	
	Quality of remanufactured products	Quality of remanufactured products	Success Factors
Product lifecycle management	Number of PLM strategies	Number of PLM strategies	Type of factors
	Types of customized innovative and sustainable circular product	Types of customized innovative and sustainable circular product	Key factors
	Quantity of closed loop life cycle	Quantity of closed loop life cycle	
	Types of life cycle pattern	Types of life cycle pattern	
	Quality of greener EoL options	Quality of greener EoL options	
	Quality of product usage data	Quality of product usage data	
Socio-economic aspects	Level of consumer involvement	Level of consumer involvement	
	Level of circular consumption	Level of circular consumption	
	Level and propensity of sustainable purchase intention	Level and propensity of sustainable purchase intention	Key factors
	Level of consumer motivation	-	
	Level of consumer environmental awareness	Level of consumer environmental awareness	
	Amount of consumer network	-	
	Quantity and ambiguity of market demand	Quantity and ambiguity of market demand	Measurable Success Factors
	Level of social responsibility	-	
	Level of consumers' behaviour	-	Key factors
	Level of validation of consumer voice	-	

4.3.2 Developing the impact model

This refinement ensures that the impact model focuses on factors that are both conceptually central to explaining how REs are triggered and practically suitable for data collection within manufacturing settings. As such, the model concentrates on internal, operational, and behaviourally relevant dynamics that can meaningfully support the detection, interpretation, and anticipation of REs during the implementation of CE strategies.

In developing the impact model, the existing factors and their established links were retained whenever they provided a clear explanation of how REs occur. However, in several cases the original links were not sufficient to describe the mechanisms through which REs manifest in a manufacturing context. For this reason, additional factors (Table 34) were introduced to enhance the model's explanatory connections and ensure a more precise representation of cause–effect dynamics.

Table 34. List of new factors included in the impact model

Impact Model factors	Type of factors	Contextual conditions
Level of demand	New factors	Operational, Economic
Cost of product	New factors	Economic
Level of production rate	New factors	Operational
Capacity of investment	New factors	Economic
Cost of virgin materials	New factors	Economic
Complexity of operations	New factors	Operational
Duration of product lifetime	New factors	Product
Support in detecting RE in manufacturing plant	Support factors	-

These newly introduced factors (Table 34) capture key drivers that influence the occurrence of REs during the implementation of circular strategies. Specifically, the level of demand, cost of the product, production rate, and capacity for investment were included to reflect the operational economic conditions that may stimulate increased production or consumption. Factors such as the cost of virgin materials, the complexity of operations, and the duration of the product lifetime were added to better represent how resource availability, process design, and product characteristics can trigger unintended rebound pathways. Additionally, a support-oriented factor—support in detecting RE within the manufacturing plant—was incorporated to emphasise the practical need for tools and capabilities that enable companies to identify and monitor REs as they emerge.

Together, these new factors strengthen the impact model by offering a more comprehensive and realistic view of how REs can materialise during CE implementation in manufacturing settings.

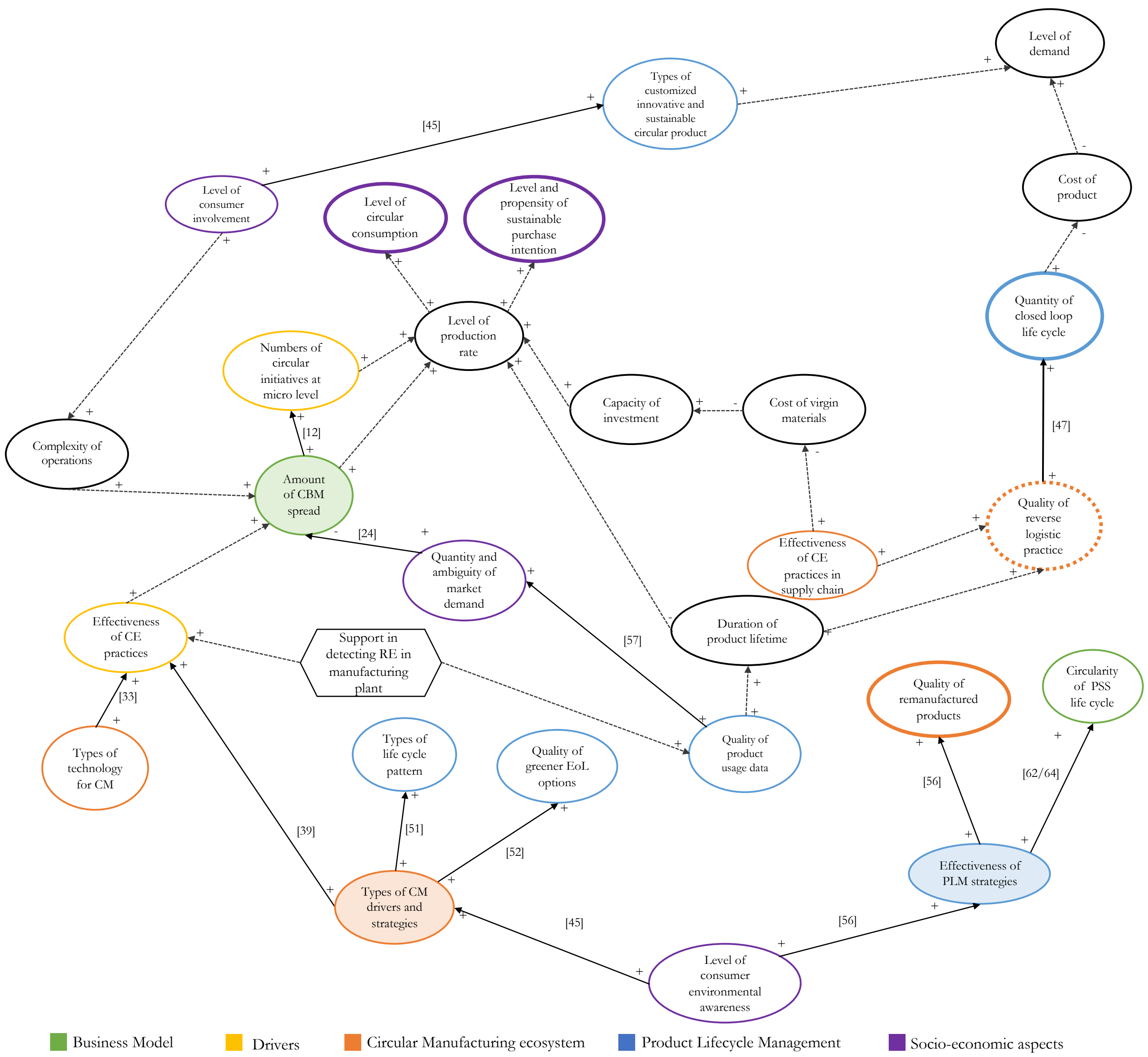


Figure 17. Impact model

To improve the readability of the impact model (Figure 17), all arrows derived from the reference model are shown in black, without distinguishing between the different types of REs that may emerge. This is intentional: the purpose at this stage is to illustrate the desired situation in which it becomes possible to detect where and how REs occur within circular manufacturing. Additionally, all new links introduced in the impact model are represented with dashed black arrows.

Starting from the bottom of the model, three factors from the reference model remain as primary driver of REs: the *level of consumer environmental awareness* (Socio-economic aspects dimension), the *types of circular manufacturing drivers and strategies*, and the *types of technologies for circular manufacturing* (both in the Circular manufacturing ecosystem dimension). Two of these retain their original connections, whereas the factor related to circular manufacturing technologies introduces new links, reflecting its expanded role in generating REs within manufacturing settings.

A key example is the connection between types of technologies for circular manufacturing and the effectiveness of CE practices (Chen et al., 2022). Increased technological efficiency may shift demand or supply structures, indirectly influence business model choices and encourage the adoption of circular business models. The factor *amount of circular business models spread* (Business model dimension) is therefore linked to the newly introduced *level of production rate*, which represents a central rebound mechanism: despite the intention to reduce environmental impacts, the adoption of CE strategies may inadvertently drive higher production volumes and resource use. This behaviour also appears in the link between production rate and the *number of circular initiatives at micro level* (Drivers dimension). Moreover, a rise in production rate feeds into two further factors—*level of circular consumption* and *level and propensity of sustainable purchase intention* (both in the Socio-economic aspects dimension)—illustrating how increased consumption driven by consumer behaviour can trigger additional REs.

Thus, the *level of production rate* becomes a pivotal element in the impact model, reached through multiple interconnected pathways. The first originates from the *quality of product usage data* (PLM dimension), which links to the new factor duration of product lifetime. Patterns of intensive or suboptimal product use may reduce product longevity, increasing replacement needs and consequently elevating production rates. The second path starts from the *effectiveness of CE practices in the supply chain* (Circular manufacturing ecosystem dimension). Improved CE performance reduces spending on virgin material, represented by the new factor lowers the *cost of virgin materials*, while increasing the *capacity of investment* (new factor), making production more attractive and economically feasible, thereby contributing to a higher production rate. Together, these pathways reinforce the centrality of the production rate in explaining how REs emerge and propagate across circular manufacturing systems.

Another key factor is the *amount of circular business models spread* (Business model dimension). As in the reference model, it remains linked to the *quantity and ambiguity of market demand* (Socio-economic aspects dimension) (Assmann et al., 2023), showing how fluctuating consumer expectations shape the diffusion of circular business models. In the impact model, this factor also connects to the newly introduced *complexity of operations*. This new factor captures the operational challenges caused by high levels of consumer involvement, which requires companies to offer more personalised, information-intensive, and service-oriented circular solutions. Such increasing complexity may push firms toward adopting circular business models as a more suitable organisational logic.

The *level of consumer involvement* (Socio-economic aspects dimension) remains connected—as in the reference model—to the *types of customised, innovative, and sustainable circular products* (PLM dimension) (Ada et al., 2023), reflecting rising consumer expectations for tailored and sustainable solutions. Building upon this link, the model introduces another new factor: the *level of demand*. When companies respond to these demands by offering more customised circular products, demand may increase, potentially triggering REs as higher production offsets the intended environmental benefits.

The *level of demand* can also be reached through another complex pathway within the impact model. This path begins with the *effectiveness of CE practices in the supply chain* (Circular manufacturing ecosystem dimension), which is now linked to the *quality of reverse logistics practices*. Implementing an adequate circular supply chain depends on effective reverse logistics. This link, already present in the reference model, leads to the factor *quantity of closed-loop life cycle* (PLM dimension) (Ada et al., 2023), which continues to explain the role of reverse flows in supporting circularity. Although these practices produce a positive effect—represented by a decrease in the *cost of product* (new factor)—the lower cost may unintentionally increase consumer demand, thereby generating a RE. Another new factor introduced in the impact model is a support element: *support in detecting RE in the manufacturing plant*. This factor is linked to both the *effectiveness of CE practices* (Drivers dimension) and the *quality of product usage data* (PLM dimension). Its position in the model is intentional. It is placed where it can provide the greatest operational value—specifically, at the interface between CE implementation activities and product-related data flows. This reflects the need for a dedicated mechanism to monitor and assess potential unintended consequences during the adoption of circular strategies. In particular, the proximity to product-usage data is essential given the influence of consumer behaviour on RE occurrence. By integrating this support factor, the model strengthens the capacity to identify, track, and interpret REs in real time within manufacturing settings.

Overall, the impact model consolidates these pathways to depict the desired situation in which REs can be systematically detected, traced, and understood throughout the implementation of CE strategies in manufacturing. By integrating both original and newly introduced factors, the model clarifies the conditions under which REs arise and pinpoints where targeted interventions may be required to mitigate unintended consequences. In this perspective, the assessment of REs becomes a key support for companies, helping them identify, understand, and manage potential negative implications linked to circular strategies. The model highlights how internal capabilities—such as process integration, data transparency, digital enablement, and workforce skills—function as critical levers to detect and mitigate RE across business processes. By anticipating where and how rebounds may emerge, the model ultimately enables more robust circular transformations that achieve intended environmental and economic benefits while minimizing the risk of unforeseen effects.

4.3.3 Developing the detection-driven tool

Once the support factor had been identified, the tool for supporting the detection of RE in manufacturing plants was developed. The process began with a rapid review of sustainability reports from three companies operating in different industrial sectors. The selected companies represented two major categories of production systems: one engaged in parts production and assembly (discrete manufacturing) and two operating in continuous process production. This selection ensured coverage of a wide spectrum of production dynamics, enabling the analysis to capture variations in reporting practices and sustainability challenges across fundamentally different processes. Reports from multiple years (2011-2024) were examined to identify recurring patterns, evolving trends, and stable information needs relevant to the development of the prototype.

Through the analysis of the sustainability reports, the most recurring sustainability objectives were extracted, such as carbon footprint reduction, energy efficiency, water stewardship, waste reduction and circularity, pollution prevention, biodiversity protection, sustainable sourcing of raw materials, eco-design and PLM, material substitution, reuse and remanufacturing, employee wellbeing, fair labour practices, diversity and inclusion, community engagement, sustainable supply chain management, ethical governance, eco-efficiency, sustainable innovation, reduction of harmful substances, energy-efficient products, durability and modularity, and consumer awareness. The list of the 17 SDGs was also included due to their strong alignment with corporate sustainability objectives. Additional spreadsheets were created to present circular manufacturing strategies (according to Acerbi and Taisch (2020)) and to classify rebound mechanisms into structural and behavioural aspects.

Overall, the detection-driven tool is composed of ten spreadsheets:

- "Dashboard" – an introductory page providing an overview of the tool, its purpose, structure, and main components.
- "User identity kit" – a sheet for collecting essential information about the company or user.
- "Questionnaire" – a set of qualitative questions related to the company and to variables that may trigger REs.
- "Sustainable development goals" – a dedicated sheet listing the 17 SDGs.
- "Circular strategy" – an overview of the main circular manufacturing strategies.
- "Rebound mechanisms" – a classification of rebound mechanisms from both producer and behavioural perspectives.
- "Results" – an automatically generated summary based on the user's responses to the questionnaire.
- "Indicators taxonomy" – a consolidated list of CE indicators selected from the literature.
- "Data" – an overview of all information entered into the tool.
- "Notes" – an area for inserting additional comments or supporting information.

The detection-driven tool begins with an introductory sheet, called "Dashboard" (Figure 18), which provides an overview of its purpose, structure, and main components. This page introduces the key concepts necessary for correct use of the tool, including definitions of CE, circular manufacturing, and REs, and offers a set of intuitive navigation links that allow users to move easily across the different spreadsheets.

Circular Economy Rebound detection-driven tool

The *Circular Economy Rebound Detection-driven* tool assesses the potential occurrence of rebound effects resulting from the implementation of circular strategies in manufacturing. It helps companies identify where the adoption of circular economy practices may unintentionally lead to negative environmental outcomes. In particular, the tool evaluates whether environmentally friendly improvements—such as increased efficiency, reuse, or recycling—might paradoxically increase environmental or resource impacts.
The tool provides a comprehensive overview of the rebound mechanisms that can be triggered by sustainability-oriented actions within the company. Moreover, it proposes key indicators that can be used to evaluate both the performance of circular strategies and the occurrence of rebound mechanisms.
It is structured as a set of targeted questions designed specifically for manufacturers operating within the circular economy, including roles such as production managers, sustainability managers, operations engineers, product designers, and circularity or environmental compliance officers. These professionals can use the tool to better detect and understand potential rebound effects.

The circular economy (CE) is a restorative and regenerative paradigm in which natural resources are preserved, resource input is minimized and optimized, and industrial systems become more efficient.
It promotes a transition from the linear “make–use–dispose” model to a circular “make–reuse–remake–recycle” model, designed to narrow, slow, and close material and energy loops. (Geissdoerfer et al., 2017)

Within this framework, circular manufacturing has emerged as a key approach to reducing the environmental burdens of the manufacturing industry. It does so through the implementation of diverse circular strategies, such as cleaner production, energy and material efficiency, product redesign, reverse logistics, and industrial symbiosis. (Acerbi and Taisch, 2020)

[Click here to know more about circular manufacturing strategies.]

Despite these positive intentions, rebound effects may occur when sustainability-oriented actions (such as those related to circular strategies) trigger systemic responses that reduce their potential environmental benefits. (Makov and Font Vivanco, 2018)
In practice, a company might achieve greater efficiency or reuse but, due to cost savings, increased production, or consumer behaviour, the total resource use or emissions still rise. (Castro et al., 2022)
An example of a rebound effect is the use of electric cars: although they are more energy-efficient, people may end up driving more, offsetting some of the environmental benefits.

To understand and prevent this, specific rebound mechanisms have been identified, describing how and why these effects are triggered.

[Click here to know more about rebound mechanisms.]

Detect potential rebound effects within your company and understand how to reduce systemic risks while enhancing the effectiveness of your circular strategies.

[Click here to start the questionnaire]

You can go directly to the “Questionnaire” tab below to start using the tool, and use the tabs below to navigate within it.

Before starting, please complete the identity kit form so we can learn more about you.

Figure 18. Dashboard page

The “Dashboard” page is followed by a user identification section collecting basic information (e.g., name, company, role, years of experience, and contact details).

Then, the main questionnaire (Figure 19) collects information about the company, the SDGs it intends to pursue, the corresponding sustainability objectives, and the circular strategies adopted to achieve them. Based on the selected strategy, users are presented with a predefined set of yes/no questions—two addressing structural rebound mechanisms and one addressing behavioural mechanisms. The two questions related to structural mechanisms correspond to two distinct variables, each accompanied by a clear definition. Together, these variables capture the two complementary aspects of the structural rebound mechanism, which—when occurring simultaneously—can give rise to the corresponding RE.

Circular Economy Rebound detection-driven tool			
Instruction			
Fill in the yellow cells that can be scrolled, as a filter, to detect potential rebound effects.			
What is the size of your company?			
Which Sustainable Development Goals (SDGs) does your company aim to contribute to?			
Which specific sustainability strategic objective has your company set to support these SDGs?			
Which circular strategies are currently implemented in your operations?		Material efficiency	
Based on the circular manufacturing strategy that has been implemented and that you have selected, please proceed to answer the following questions.			
8-9-14			
	VARIABLE	**QUESTION**	**ANSWER**
1	*Cost of production*	Have efficiency improvements resulted in a lower unit cost of production?	
a	Represents the cost incurred to produce one unit of product.		
	Product sales volume	Have you noticed an increase in sales volume?	
b	Quantity of product sold over a specific period.		

Figure 19. Questionnaire page with an example of question

Their responses feed into the results sheet (Figure 20), which automatically identifies the potential rebound mechanisms associated with the answers provided. The results also include a set of potential indicators commonly used to assess CE performance, as discussed in the Section 3.3.2. These indicators are linked to the specific aspects targeted by the selected circular strategies and to the rebound mechanisms identified through the questionnaire responses. These indicators are intended to provide guidance for assessing circular strategies during their implementation and to serve as initial suggestions to support early monitoring of potential RE occurrences by tracking one or more relevant variables. Moreover, the results page provides a direct link to the corresponding set of CE performance indicators, each accompanied by definitions and formulas extracted from the literature, allowing users to explore the metrics in greater depth.

Indicators to monitor the circular strategy selected:		**List of potential rebound mechanisms that may arise based on your answers:**		**Indicators to monitor each rebound mechanism considered**		
Circular strategy	Material efficiency	**1**		**Rebound mechanism**	Consumption efficiency	Cross-factor/ Cost-dependent output
		2				
List of indicators considered:		**3**				
Additional cost for Environmentally-friendly products and materials		**4**		**Indicators**	Reduction in material cons	Additional cost for Envir
Amount of emissions in air		**5**			Time for disassembling pro	Material cost per unit of product
Circular Economic Value (CEV)		**6**			Total material consumptio	Number of products with take-back policies
Circular Economy Monitoring Framework (CEMF)		**7**				Rate at which products are returned after leasing period
Circularity Index (CI)		**8**	Consumption efficiency			Reduction in material consumption (%)
Circularity Indicator Project (ICT)		**9**				Total material consumption (weight or volume)
Circularity material indicator (CIRC)		**10**				Total net output of material sent to disposal in kg
Input-Output Balance Sheet (IOBS)		**11**				
Material Circularity Indicator (MCI)		**12**				
Material cost per unit of product		**13**				
Material Reutilization Part (C2C)		**14**	Cross-factor/ Cost-dependent output			
Number of products that are recycled or upcycled		**15**				
Packaging costs		**16**				
Rate at which products are returned after leasing period		**17**				

Figure 20. Overview of the results page

Another sheet compiles all the data entered in the form, providing a consolidated overview of the responses. A final notes section enables users to record additional information related to sustainability objectives, indicators, metrics for assessing circular performance, or any unintended consequences observed during the implementation of circular strategies.

Together, these elements ensure that the detection-driven tool systematically supports the identification, understanding, and preliminary monitoring of potential REs within manufacturing environments, helping companies become aware of the unintended negative consequences that may arise during the implementation of CE strategies.

4.4 Results from Stage 4: Descriptive Study II

This section presents the results of the final stage of the DRM—*Descriptive Study II*—focusing on the validation of the tool and the integration of expert feedback into the revised version.

Across the expert interviews, several valuable insights were collected, and all experts agreed on the relevance, usefulness, and timeliness of the detection-driven tool, acknowledging both its conceptual scope and the clarity with which it was presented. They highlighted that a tool specifically designed to detect potential REs in circular manufacturing is currently missing in both research and practice, and emphasised its potential to support companies in anticipating the detection of unintended consequences of CE implementation. In addition to structural and functional suggestions, several experts also provided comments on the clarity, coherence, and readability of the written content. These comments (Table 35) were integrated by refining definitions, improving explanations, and ensuring a more consistent use of terminology across the tool, thus enhancing its overall communicative quality. Their feedback contributed substantially to improving the tool's structure, content, and usability, making it more intuitive for practitioners while preserving its scientific rigour.

Table 35. Summary of experts' feedback

Category	Feedback
Dashboard clarity	Clarify the overall purpose and scope of the tool; include explicit references to sources; provide clearer definitions of CE and REs supported by an illustrative example.
User identification	Clearly define the target audience; include a structured list of job positions, roles, and professional profiles to capture organisational context.
Questionnaire clarity	Refine ambiguous questions; explain why structural rebound mechanisms require two variables/two questions; add direct links to related spreadsheets (e.g., SDGs, CE strategies). Experts also suggested automated completion checks, visual alerts for empty fields, and "TO BE FILLED" prompts.
Indicators	Strengthen traceability between CE strategies and performance metrics; provide a searchable and filterable database of indicators to support indicator selection and interpretation.
Results presentation	Simplify and reorganise the results section to avoid clutter and reduce the risk of misinterpreting CE indicators as the primary output. Emphasise rebound mechanisms and potential early-warning indicators. Experts also suggested adding intermediate risk levels and prioritisation guidance for REs, though these were not feasible in the current version.

Navigation	Improve interconnectedness between CE strategies, SDGs, and other sections of the tool. Experts recommended transitioning from Excel to a web-based platform or integrating the tool into corporate dashboards for enhanced usability.

Experts highlighted the need to include explicit references to the sources used for defining REs, given the variety of interpretations and terminologies available in the literature. They also recommended providing a clearer and more accessible definition of REs—supported by illustrative example—so that users with no prior familiarity with the concept can fully understand it before responding to the questionnaire. Responding to these comments, the definition section was enriched, an example was added, and the underlying references were transparently integrated.

Following suggestions to improve the overall structure, the second page contains the user identity kit, where respondents can enter their personal and organisational information. Experts emphasized the importance of clearly identifying the tool's intended audience; therefore, a predefined list of roles and professional profiles was included—ranging from sustainability managers and operations engineers to CE specialists and strategic decision-makers—to guide users more effectively and ensure that responses are provided by individuals familiar with the company's sustainability initiatives.

Several questions in the main questionnaire were refined to improve clarity and reduce ambiguity, and direct links to the SDGs and circular strategy pages were added to strengthen internal coherence and improve navigation across the tool. Experts also recommended adding a dedicated spreadsheet listing all 17 SDGs with their official names and definitions, which was implemented to help users more accurately select and interpret the SDGs relevant to their context and ensure alignment with corporate sustainability frameworks. To better support users in retrieving CE performance indicators, two dedicated spreadsheets were introduced: one displaying indicators associated with the selected circular strategy, and another presenting the complete set of indicators identified in the literature, searchable via a filter. This addition responds to experts' need for traceability between CE strategies, expected improvements, and available metrics.

For the structural rebound mechanisms, a note (Figure 21) was added to clarify why each mechanism is assessed through two variables—and consequently two questions—reflecting the dual dimensions that together enable the mechanism to materialise. This explanation enhances transparency, helping users understand how structural mechanisms operate and why both components need to be evaluated.

When you find two questions—one for each variable—it is because this type of negative consequence becomes visible only by examining two different aspects. Considering both aspects together allows you to identify the potential occurrence and the potential undesired consequence.

Figure 21. Annotation for rebound mechanism questions

The results page was reorganised and clearly separated from the section on CE indicators to enhance readability and avoid confusion between the questionnaire outcomes and the contextual information provided by CE metrics (Figure 22).

Here you can find the circular strategy selected in the questionnaire.	
Circular strategy	Circular design practices
Below is a list of indicators associated with the selected circular economy strategy.	
List of possible indicators:	
Amount of reused/recycled materials in new designs	
Circularity Calculator (CC)	
Longevity	
Number of products that are recycled or upcycled	
Percentage of "Designing for deconstruction" strategies	
Percentage of products designed on circular economy principles	
Revenue from upgrade, repair and maintenance services	
Revenues from eco-products	
[To know more about the indicators click here]	
If you think that any additional indicators are missing and could be useful in this tool, please	

Figure 22. Circular strategy and indicators page

To prevent misinterpretation, the list of potential indicators—adapted from those commonly used to assess CE performance—was accompanied by a disclaimer stating that these indicators serve only as preliminary suggestions to support early data collection on potential rebound mechanisms and are not intended as definitive or comprehensive measurement tools (Figure 23). Their inclusion is meant solely to help users monitor one or more of the variables that characterise each mechanism, thereby facilitating an initial understanding of where REs may arise within companies.

Moreover, each rebound mechanism detected through the questionnaire is now accompanied by a short definition and a direct link to the detailed mechanism page, improving interpretability and navigation, and helping users quickly connect their answers to the theoretical explanation of how each mechanism operates.

List of potential rebound mechanisms that may arise based on your answers:			Indicators to monitor each rebound mechanism considered				
1			Rebound mechanism	Consumption efficiency	Re-design	Response efficacy bias	Contributions ethics
2			The following list includes potential indicators commonly used to assess circular economy performance, which may also help in initially monitoring the possible occurrence of negative aspects (i.e., rebound effects).				
3							
4			Indicators	Reduction in material cons	Amount of reused/recyc	No indicators identified	No indicators identified
5				Time for disassembling pro	Number of products that are recycled or upcycled		
6				Total material consumptio	Percentage of "Designing for deconstruction" strategies		
7					Percentage of products designed on circular economy principles		
8	Consumption efficiency	increasing demand for resources.			Time for disassembling products		
9							
10							
11							
12							
13							
14							
15							
16							
17							
18	Re-design	total resource use.					
19							
20							
21							
22							
23							
24	Response efficacy bias						
25	Contributions ethics						
26							
27							
28							
29							
30							
	[Click here to know more about the rebound mechanisms]						

Figure 23. Rebound mechanism result page

Some suggestions, however, were not feasible within this version of the tool. These included introducing intermediate answer options to express different levels of rebound risk—an approach that experts agreed would be valuable but is currently impractical due to the qualitative nature of the questionnaire, the absence of quantitative data, and the lack of established thresholds for evaluating rebound likelihood. Implementing such graded assessments would require a more advanced methodological foundation, supported by extensive empirical datasets and statistical modelling to ensure reliability and validity. Similarly, providing prioritisation guidance for decision-makers on which rebound mechanisms to address first was not possible at this stage, as priority-setting would depend on company-specific factors (e.g., operational structure, strategic objectives, supply-chain dynamics) that extend beyond the scope of a general-purpose tool. Experts recognised that these features represent important long-term opportunities but would necessitate additional research phases, pilot applications in industrial settings, and iterative refinement.

Several technical improvements suggested by experts also could not be incorporated due to limitations inherent to the Excel-based format used for the tool. For instance, some experts recommended implementing automatic checks to ensure all required questions are completed, such as error prompts when fields are left empty or visual alerts (e.g., "TO BE FILLED") next to unanswered items. While these functions would significantly enhance usability and reduce incomplete submissions, they are difficult to implement robustly in Excel without advanced scripting or platform-specific automation. As a result, such dynamic validation features were deferred for future versions of the tool, ideally within a digital environment more suitable for interactive input validation.

Additionally, the development of a more navigable or fully digital version of the tool—such as a web-based platform, interactive decision-support software, or integrated module within corporate sustainability dashboards—was considered highly desirable but could not be implemented within the current project constraints. Creating such technological solutions would require dedicated programming resources, user-interface design, and testing cycles. Nonetheless, experts emphasised that a digital evolution of the tool would greatly enhance accessibility, facilitate real-time data integration, and support broader adoption within companies, making it a promising direction for future iterations.

Overall, the incorporated feedback significantly improved the clarity, coherence, and practical applicability of the tool. The final version is more user-friendly, theoretically grounded, and aligned with industrial needs, strengthening its potential to support companies in detecting and understanding potential REs during the implementation of circular strategies in manufacturing. By combining conceptual depth with practical usability, the tool offers a structured way for organisations to reflect on unintended sustainability trade-offs, anticipate systemic responses to CE initiatives, and make more informed decisions. As such, it represents a meaningful contribution to both academic research and practical sustainability management, laying a foundation for future advancements in RE assessment within circular manufacturing.

During the two workshop-style interview sessions conducted with industrial experts, the detection-driven tool was recognised as a valuable instrument for assessing whether current or planned CE strategies may lead to negative or unintended effects. The tool was perceived as a practical guide for minimising the potential occurrence of REs by supporting early-stage reflection on the risks associated with circular initiatives.

Although the manager involved in the first interview was not yet implementing circular strategies within the company's current processes—and therefore could not directly apply the tool—the expert acknowledged its relevance and potential applicability to sustainability-oriented projects, such as those aimed at reducing resource consumption and environmental impacts.

During the second interview, which was organised to present the detection-driven tool to an expert actively leading sustainability projects within the company, the expert identified a concrete opportunity to apply the tool within an ongoing industrial project—specifically one focused on optimising and reducing water consumption. This discussion highlighted how the tool could support a more accurate estimation of potential REs. The second session therefore reinforced the perceived usefulness of the tool, particularly as a means of raising awareness of possible negative implications of CE strategies that had not previously been considered.

5. Discussions

This study demonstrates that REs can arise as unintended consequences of implementing CE strategies in manufacturing. By progressing through the stages of the research methodology, it becomes possible to trace where and how REs emerge as firms transition toward circular models. The first step defines the five dimensions in which REs may occur—Business model, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects—thereby structuring the research domain and identifying key elements relevant for detecting potential rebounds. Within the Business model dimension, the adoption of circular business models aims to generate environmental, social, and economic benefits, yet may unintentionally generate REs. PSS, for example, can trigger rebounds due to reduced ownership, lower user responsibility, or overconsumption. However, circular business models still lack integrated performance measurement systems for environmental and social impacts. The analysis of CE performance assessment methods revealed that existing approaches remain largely focused on material efficiency and environmental impact quantification, with limited attention to cross-process dynamics and unintended consequences. This supports the need for complementary frameworks, such as the detection-driven tool proposed in this thesis, to identify potential rebound mechanisms that current assessment methods overlook. The Drivers dimension highlights how organisational, institutional, economic, and behavioural forces may foster CE adoption while also amplifying REs if not properly managed. In addition, this dimension is weakened by a lack of empirical data, limited tools to measure or prevent REs, and widespread unawareness or insufficient education regarding rebound implications. The Circular manufacturing ecosystem dimension emphasises how technological interdependencies, supply-chain interactions, and actor collaborations can reshape resource flows and process dynamics, inadvertently increasing resource use. Here, the weak understanding of how REs diffuse across interconnected systems and complex PSS lifecycles signals an urgent need for research capable of guiding policymaking. The PLM dimension shows that lifecycle decisions—especially repair, remanufacturing, or recycling at end-of-life—may stimulate new production or consumption. In addition, the PLM dimension identifies design as a decisive lever for preventing REs but notes the persistent shortage of empirical data and indicators needed to evaluate CE benefits and anticipate rebound pathways, making empirical validation a key research gap. Finally, the Socio-economic aspects dimension demonstrates that consumer responses to perceived sustainability improvements may paradoxically increase overall consumption, underlining the need for regulatory mechanisms to manage REs during CE transitions. Together, these dimensions clarify where attention must be focused to prevent or mitigate REs throughout CE implementation.

Across the circular strategies analysed, both producer decisions and consumer behaviours activate a wide range of rebound mechanisms. Although these mechanisms often converge on similar outcomes—typically increased production or consumption—they operate through distinct causal pathways including motivational dynamics, efficiency gains, cost reductions, and market adjustments. Linking mechanisms to specific CE strategies offers a diagnostic basis for anticipating where negative feedback loops may occur. The comparative analysis across business model, product design, production, and procurement processes shows that production and procurement are particularly vulnerable: production often experiences efficiency-driven rebounds that increase throughput, while procurement—especially supply-chain restructuring—can stimulate resource-intensive market expansion. In contrast, business model innovation and product design mainly trigger behavioural or perception-driven rebounds. Ten mechanisms that were either too individualistic or too systemic were excluded to maintain firm-level relevance. These distinctions confirm that REs are unevenly distributed across processes and therefore require process-specific mitigation strategies spanning regulatory measures, supply-chain governance, and behaviour-oriented interventions. By incorporating performance assessment methods, this mapping can be quantitatively reinforced, providing practitioners with measurable proxies to detect early signs of efficiency-driven or perception-driven REs.

The in-depth literature review enabled the identification of characteristic factors within each of the five dimensions and the mapping of relations between them. These interconnections expand current CE–RE knowledge, which has traditionally examined dimensions in isolation. For instance, strong relations between Business models and Socio-economic aspects confirm earlier findings that consumer acceptance affects circular business model uptake while showing that such interactions can unintentionally generate REs through increased demand. Similarly, relations between Business models and Drivers illustrate that while economic and regulatory drivers support circular business model adoption, they may simultaneously amplify rebound dynamics. Links between Drivers and the Circular manufacturing ecosystem confirm the influence of regulation and institutional support on CE adoption while revealing their potential to trigger REs. Strong correlations between PLM and Socio-economic aspects further demonstrate that consumer behaviour can counteract lifecycle decisions aligned with CE principles. More complex multi-dimensional interactions—such as those involving Business model, Drivers, Circular manufacturing ecosystem, and Socio-economic aspects—underline the multi-layered nature of CE–RE dynamics. Evaluating these relations through the lens of REs shows that direct rebounds mainly arise from interactions with consumer perceptions and demand; indirect rebounds originate from Circular manufacturing ecosystem and PLM relations; economy-wide rebounds stem from interactions between Drivers and the Circular manufacturing Ecosystem; and transformational rebounds emerge from systemic relations between Business Model and Drivers. Recognising these patterns strengthens the design of targeted mitigation strategies.

Building on these insights, the reference model provides a comprehensive representation of how REs may manifest across the CE–RE dimensions. Eleven links were associated with indirect REs, typically involving PLM or circular manufacturing strategies that improve efficiency but shift environmental burdens elsewhere. Nine links generated direct REs, often through interactions between Business model or Drivers and Socio-economic aspects factors where perceived gains increase demand. Six links produced economy-wide REs by influencing broader market dynamics, while five triggered transformational REs, reflecting systemic changes in production systems or consumer practices. The factors within the model serve as analytical nodes for detecting where REs originate and how they propagate across manufacturing systems.

To deepen this understanding, seven categories of research gaps were identified. Industrial applications emerge as the highest priority, reflecting the limited empirical evidence on how REs materialise in practice. Additional gaps relate to drivers, technology potential, performance assessment, and consumer behaviour—areas that hold significant influence over CE implementation and RE emergence. The findings from the CE performance assessment literature reinforce this gap: despite the rapid development of new methods, most tools still prioritise material and energy efficiency indicators, rarely integrating behavioural or systemic variables capable of signalling rebound risks. This confirms that existing CE assessment frameworks alone are insufficient for capturing unintended effects and must be complemented with RE-oriented diagnostic approaches. Interviews with eight automotive-sector practitioners helped address industrial gaps. Companies reported adopting circular strategies—such as component recovery and recycled-plastic use—in response to regulatory pressures and measured benefits using LCA-based KPIs. However, they did not recognise that circular improvements themselves could generate REs, focusing instead on economic and operational challenges. This aligns with the literature and highlights a general lack of RE awareness within industry, underlining the need for targeted guidance to avoid unintentionally offsetting CE benefits.

The analysis of rebound mechanisms across the CE–RE dimensions identified seventeen mechanisms. The Drivers dimension emerged as the most influential, triggering five mechanisms and acting as a major origin of REs. PLM triggered four mechanisms, illustrating how lifecycle efficiency improvements can propagate via increased supply or consumption. The Circular manufacturing ecosystem dimension includes both cause and effect factors, indicating its dual enabling and reactive nature. The Business model dimension triggered fewer mechanisms, though circular business model and PSS remain important sources of rebounds. The Socio-economic aspects dimension reflected primarily effect factors driven by consumer behaviour and market responses. These findings identify which factors require the closest monitoring to detect and manage RE risks.

To support industrial application, the factors and links from the reference model were categorised into the four classes of the circular manufacturing data model—product, process, management, and technology. The management category is the most populated, demonstrating the strong influence of organisational decisions, regulation, and consumer behaviour on CE adoption and RE emergence. The technology category spans all CE–RE dimensions, confirming the central role of PLM data, digital tools, and production technologies in both enabling and preventing REs. The process category, dominated by Circular manufacturing ecosystem factors, highlights the importance of operational and supply-chain actions in shaping RE risks. The product category, although smaller, reveals particular vulnerability to REs driven by consumer responses to CE-oriented product development. Linking the CE–RE reference model with the circular manufacturing data model reinforces the importance of structured data collection to support RE detection and mitigation throughout circular implementation.

Finally, the impact model was developed to provide a comprehensive representation of the desired situation in which REs associated with CE implementation in manufacturing can be systematically detected. The model highlights where attention should be directed to identify potential REs during the adoption of circular strategies, introducing new links and factors that enhance the explanatory power of the original reference model. These additions allow a more detailed and transparent understanding of how REs may emerge in this context, while also clarifying the role of support actions.

Specifically, eight new factors were incorporated to better explain the causes and effects generated by CE actions that may lead to rebound. These new factors reflect the most visible RE manifestations—such as increases in demand, production, and resource use—and make explicit how these effects stem from existing factors in the reference model. Moreover, the introduction of nineteen new links enriches the model by capturing the full range of RE dynamics in circular manufacturing, thereby making it clearer where and how these effects may arise.

The resulting impact model provides practical support for detecting REs by offering a more precise representation of how certain sustainability-oriented actions—intended to improve efficiency—may instead lead to higher resource consumption or increased production. It also identifies the points in the system where a support factor, conceptualised as a detection tool, should be integrated. This support factor is connected to product lifecycle data, enabling the monitoring of changes in products over time, and to CE practices, ensuring that environmental, economic, and social benefits are effectively achieved and not undermined by unintended rebound dynamics.

Finally, the detection-driven tool developed in this research represents an important first step toward operationalising the detection of REs within circular manufacturing—a domain in which conceptual understanding is steadily advancing, yet practical assessment instruments remain scarce. By integrating circular strategies, sustainability objectives, SDGs, and a comprehensive set of rebound mechanisms, the tool provides a structured and accessible framework through which companies can begin identifying potential unintended consequences arising from CE implementation. Its value lies not only in its diagnostic function but also in its capacity to support learning and awareness-building among practitioners. This directly addresses one of the critical barriers identified in the literature: the limited understanding of what REs are, how they arise, and why they can undermine CE efforts in industrial settings.

A key strength of the tool is its grounding in both theory and practice. The incorporation of systematically reviewed rebound mechanisms ensures strong alignment with contemporary academic discourse, while the iterative validation with experts anchors the tool in real operational needs and practical constraints. This dual perspective strengthens its credibility and demonstrates the feasibility of translating complex rebound dynamics into a structured and actionable detection process. Furthermore, the integration of SDGs and CE performance indicators enhances its relevance for companies striving to align CE initiatives with established sustainability frameworks and reporting practices, making the tool compatible with organisational decision-making contexts.

The design of the questionnaire—explicitly distinguishing between structural and behavioural rebound mechanisms—contributes to a more holistic understanding of how REs can be triggered. By prompting users to reflect on specific organisational practices, efficiency improvements, behavioural responses, and strategic decisions, the tool encourages companies to consider aspects of CE implementation that are frequently overlooked. This reflective process is, in itself, a significant outcome: before REs can be measured or mitigated, they must first be recognised and conceptually understood within the organisation.

The qualitative nature of the questionnaire implies that the results should be interpreted as indicative rather than quantitative. Rather than calculating rebound magnitudes, the tool identifies which mechanisms may potentially be triggered and highlights the key variables that should be monitored to support early detection. This is further reinforced through the association of each mechanism with relevant circular performance assessment indicators, which serve as practical proxies for observing early signals of rebound within manufacturing systems.

In addition, the feedback collected during expert validation from both academia and industry played a crucial role in refining the final version of the tool. Usability was enhanced through the reorganisation of spreadsheets, clearer navigation pathways, and the inclusion of explanatory notes and definitions designed to support users who may be unfamiliar with RE terminology. Several textual sections were rewritten to improve precision and clarity, while additional resources, such as expanded SDG definitions, indicator repositories, and integrated links, were incorporated to facilitate a more informed completion of the questionnaire. Moreover, industrial experts highlighted the tool's strong applicability in maximising the benefits that companies aim to achieve through different types of sustainability projects involving CE strategies. They emphasised its potential to support decision-making processes, enhance the strategic alignment between circular initiatives and corporate objectives, and identify priority areas where REs may compromise expected outcomes. According to practitioners, the tool also offers practical value in cross-functional contexts, facilitating communication among departments, improving the consistency of sustainability assessments, and enabling a more structured evaluation of CE-related interventions across the organisation.

Overall, the detection-driven tool now offers a more coherent, user-friendly, and conceptually robust framework, strengthening its potential to support companies in detecting and understanding potential REs during the implementation of circular strategies in manufacturing. While further development—particularly toward digitalisation and quantitative assessment—remains an avenue for future work, the current version already makes a meaningful contribution to both academic research and practical sustainability management by laying the foundations for systematically addressing REs in circular manufacturing.

5.1 Contributions to knowledge and practice

This study offers several contributions to both research and practice by clarifying where REs may arise within circular manufacturing and how they can be systematically detected and mitigated.

The first contribution is the systematic organisation of knowledge across the CE–RE domain. Through the systematic literature review, five key dimensions where REs may emerge (i.e., Business model, Drivers, Circular manufacturing ecosystem, PLM, and Socio-economic aspects) were identified and characterised. This classification provides a coherent framework for researchers, indicating where to focus future investigations and which vulnerabilities are most critical. For practitioners, it highlights the organisational, behavioural, and systemic factors that may undermine circular strategies. The complementary systematic review of CE performance assessment methods strengthens this contribution by clarifying which existing methods are most frequently used, what variables they measure, and where methodological blind spots remain. Specifically, it reveals that current CE assessment approaches rarely account for rebound-related dynamics, further validating the need for RE assessment tools.

A second major contribution is the mapping of circular manufacturing strategies across business processes and the integration of both producer- and consumer-related rebound mechanisms. This dual perspective clarifies how efficiency gains, behavioural responses, or market adjustments may cause well-intentioned CE actions to backfire.

Linking rebound mechanisms to specific business processes produces a structured and replicable diagnostic framework for evaluating the adoption of circular strategies.

In addition, the review of CE performance assessment methods further complements this framework by showing that CE measurement tools typically capture isolated resource-efficiency improvements but not the cross-process interactions that often give rise to unintended REs. Integrating assessment indicators with rebound mechanisms therefore enhances the robustness and operational relevance of the diagnostic framework.

From a practical standpoint, the study provides frameworks to anticipate and mitigate RE risks. Illustrative examples and process-specific recommendations help managers detect early signals of REs, for instance, efficiency-driven increases in output, behavioural responses to new product designs, or procurement-related market expansions. The study also emphasises the need for governance mechanisms in circular supply chains, performance indicators aligned with eco-efficiency standards, and business model incentives that discourage uncontrolled expansion or unintended resource intensification. Findings from the CE performance assessment literature support this need. Although methods such as LCA, MFA, and MCDM provide valuable insights into environmental and resource-related performance, they do not capture the systemic or behavioural factors that drive REs. Managers should therefore complement traditional CE assessment approaches with RE-oriented diagnostic tools to ensure a comprehensive evaluation.

For managers, the study provides actionable guidance for selecting CE performance assessment methods aligned with operational and sustainability goals. For instance, LCA remains the most widely applied tool for environmental impacts across lifecycle stages, while MFA supports material flow monitoring. Emerging methods can further address specific circularity objectives and track RE-related effects. This enables practitioners to measure progress, detect potential rebounds, and make informed decisions on process and product interventions.

The second stage of the study advances theoretical understanding by identifying dimension-specific factors and mapping their interconnections, thereby uncovering pathways through which direct, indirect, economy-wide, and transformational REs may arise. The resulting conceptual maps and the CE–RE reference model strengthen theory development by showing how circular actions propagate across micro, meso, and macro levels. These contributions reinforce the study's positioning within the broader research on industrial sustainability transitions, socio-technical systems change, and the systemic consequences of CE implementation in manufacturing. Practically, these maps function as early warning tools for practitioners, helping in recognising circular interventions that may inadvertently increase production, resource use, or consumption. The CE performance assessment review reinforces this contribution by showing that existing methods lack the capacity to detect early-warning signals associated with rebound pathways. By organising indicators according to variables, lifecycle stages, and TBL perspectives, the review provides a foundation for enriching the reference model with more operational monitoring capabilities.

The study also identifies research gaps across seven thematic areas, establishing a research agenda to support the CE transition. These gaps reveal priority areas for innovation, such as industrial applications, performance measurement, monitoring technologies, and consumer behaviour analysis, insights that are relevant to both researchers and practitioners.

The interviews conducted in the automotive sector provide a real-world perspective on CE adoption. Findings indicate that companies primarily respond to regulatory pressures and use LCA-based KPIs to assess benefits. Yet, they often overlook the possibility that circular practices themselves may generate REs, revealing a critical awareness gap. These insights help practitioners understand regulatory challenges, opportunities for innovation, and points where CE practices may lead to unintended outcomes.
The third stage strengthens the contribution by linking the CE–RE reference model to specific rebound mechanisms, differentiating between cause and effect factors. This classification clarifies why REs emerge and highlights where monitoring should be prioritised. It supports practitioners in identifying high-risk circular initiatives and designing more effective strategies.
Additionally, categorising the reference model links into the four classes of the Circular manufacturing Data Model (product, process, management, and technology) provides guidance on which data should be collected to detect and prevent REs. This integrated framework supports systematic risk assessment, helps managers focus on critical data streams, and strengthens evidence-based policymaking.
Finally, the impact model developed in this study provides a structured approach to detecting REs within circular manufacturing by introducing new factors and links that clarify how rebound dynamics emerge. These additions enhance the theoretical understanding of RE occurrence, enabling researchers to identify the main effects triggered by circular strategies and explore targeted mitigation solutions. From a practical perspective, the model functions as an analytical framework that helps practitioners pinpoint where REs are likely to arise and understand the role of the support factor in monitoring them. By highlighting where RE detection tool should operate and which data are most relevant, the model guides the development of effective measurement and monitoring systems.

The detection-driven tool's broader contribution is noteworthy, as it provides a foundation for bridging the gap between theoretical discussions on REs and the practical challenges faced by companies adopting CE strategies. It stimulates cross-functional dialogue within firms, raises awareness of RE risks, and supports the development of more resilient and effective circular strategies.
From a knowledge standpoint, the tool advances the field by operationalising rebound mechanisms that have long been examined predominantly at a conceptual level. It transforms theoretical constructs into an applied detection tool, enabling a clearer understanding of where and how REs may emerge within manufacturing systems. Its integration of CE strategies, SDGs, and rebound theory contributes a more holistic and interconnected perspective, clarifying the relationships between sustainability objectives, circular practices, and potential unintended consequences. This structured integration also helps to reduce the conceptual fragmentation commonly noted in the rebound literature, fostering greater consistency in terminology, definitions, and analytical boundaries. This operationalisation is particularly significant given that most CE performance assessment methods prioritise quantitative efficiency indicators without addressing rebound mechanisms. The tool therefore fills a critical gap by explicitly linking CE strategies, performance indicators, and RE mechanisms in a format accessible to practitioners.

In practice, the detection-driven raises awareness within companies in a more concrete and comprehensive way by supporting the early-stage identification of unintended consequences associated with CE implementation. Its structured questionnaire guides users to systematically reflect on efficiency gains, behavioural dynamics, design practices, and supply-chain decisions, areas where REs often originate but are seldom examined within organisational settings. In doing so, the tool strengthens internal awareness and builds organisational capacity to anticipate and mitigate risks related to rebound behaviour.

The inclusion of SDGs and CE performance indicators ensures alignment with widely adopted sustainability frameworks, making the tool immediately relevant for organisations already engaged in environmental reporting and strategic planning. This alignment also helps companies maximise the benefits of their sustainability projects by providing a clearer understanding of how circular initiatives contribute to broader environmental and socio-economic objectives.

The mechanism-based structure further assists practitioners by highlighting key variables to be monitored in order to detect early signals of potential rebound. This supports more informed and resilient decision-making, enabling an initial assessment of the most relevant aspects linked to RE occurrence. This aligns with the findings from the CE performance assessment literature, which shows that while indicators exist for monitoring materials, energy, and emissions, no current assessment framework provides structured guidance for identifying REs triggers. The detection-driven tool developed in this thesis addresses this gap by linking CE indicators with RE mechanisms, enabling a more anticipatory and preventive evaluation.

Moreover, the detection-driven tool facilitates internal collaboration by prompting dialogue among the organisational units involved in sustainability and CE initiatives. Its use encourages a shared understanding of how circular strategies interact with operational realities, behavioural patterns, and systemic constraints, thereby fostering a more integrated and cohesive approach to CE adoption.

Importantly, the refinement of the tool through expert validation significantly enhances its usability and practical relevance. Experts' suggestions led to clearer definitions, improved navigation pathways, better alignment between sections, and a more intuitive structure, ultimately making the tool more accessible to practitioners who may not have specialised expertise in REs or CE.

Overall, the detection-driven tool represents a meaningful advancement in both research and practice. It operationalises a complex and underexplored sustainability challenge, supports organisations in anticipating undesired effects of CE strategies, and establishes a solid foundation for more sophisticated approaches to rebound detection and management in circular manufacturing.

5.2 Managerial and policy implications

This research advances both managerial practice and policy design by highlighting the critical need to integrate RE considerations CE strategies.

Without an explicit integration of RE awareness into the design, implementation, and monitoring of CE initiatives, circular transitions risk unintentionally reinforcing linear outcomes.

From a managerial perspective, the study underscores that the implementation of circular strategies within business processes requires careful planning, continuous monitoring, and rigorous evaluation to prevent REs that undermine sustainability goals. For each business process, specific recommendations have been formulated and aligned with the corresponding circular strategies.

Managers should design incentive systems and performance indicators that discourage uncontrolled business expansion. When circular business models grow beyond optimal capacity, they may become environmentally inefficient or economically unsustainable. Service-based or leasing models, in particular, require monitoring systems to prevent the overexpansion of service assets that could increase total production and trigger indirect or economy-wide REs. When adopting lean approaches, cleaner production, or material and energy efficiency strategies, managers should align operations with recognised eco-efficiency and environmental management standards. These frameworks provide an initial organisational foundation for detecting early signals of REs, such as when efficiency improvements lead to increased total output or when material substitution unintentionally drives higher resource use. Decision-makers should incorporate principles of durability, repairability, sufficiency, and responsible modularity, drawing on standards aligned with emerging European Ecodesign regulations. Such principles help reduce behavioural or systemic REs related to premature product replacement, excessive modular upgrades, or the unnecessary production of spare components. The factors and links offer additional guidance, helping managers and decision-makers understand which CE dimensions interact when a specific design-related factor is activated. Managers should promote transparent coordination within closed-loop supply chains and industrial symbiosis networks. Governance mechanisms, supported by monitoring and reporting systems, are necessary to ensure that material exchanges produce net environmental benefits rather than stimulating redundant production or excessive recirculation of secondary materials, both of which can trigger REs in B2B and industrial contexts.

The reference model offers an additional diagnostic framework through which managers can understand how elements within the organisation interact to generate REs. By recognising different types of REs, practitioners can anticipate where efficiency improvements may unintentionally increase demand or resource use and design mitigation strategies accordingly. This study also highlights specific managerial insights relevant to the automotive sector, such as the risk that circular strategies may lead to price reductions that stimulate demand or challenges related to integrating recycled materials into production.

Finally, the detection-driven tool developed in this research provides managers with a practical, actionable solution for identifying potential REs. By making rebound pathways visible, the tool stimulates cross-functional collaboration among sustainability departments, operations managers, designers, and decision-makers. The set of conceptual maps and clustered factors further alerts practitioners to the types of REs that may occur, supporting more informed strategic planning and enabling companies to anticipate and mitigate risks before implementation.

The research also offers significant policy implications. Many existing CE policies, particularly those centred on efficiency, recycling, or PSS models, still lack explicit RE considerations and may inadvertently stimulate linear outcomes. This study demonstrates the urgency of developing RE-informed policy frameworks that align regulatory strategies with circular practices.

Introducing resource caps, efficiency thresholds, and monitoring requirements, such as within the Industrial Emissions Directive, can prevent the unintended overuse of materials following process improvements. Regulations for sustainable products, including forthcoming durability and reparability directives, should explicitly integrate RE assessments. This includes analysing market expansion risks associated with longer product lifetimes, modular upgrades, or increased service offerings. Multi-level governance frameworks and stable funding mechanisms for industrial symbiosis networks are essential to coordinate stakeholders, balance collaboration incentives, and avoid overcapacity or duplication of production infrastructure. Policy instruments promoting service-based or leasing models should include monitoring mechanisms to prevent the uncontrolled expansion of service assets, which may increase total production volumes and trigger systemic REs.

Policymakers can use insights from CE performance assessment literature to establish indicators for monitoring CE adoption and detecting potential REs at regional or national levels. By tracking material flows, energy efficiency, and social outcomes, regulatory frameworks can identify when efficiency gains or circular strategies inadvertently trigger higher resource consumption or market expansions. This informs guidelines, incentives, and enforcement mechanisms that align industrial practices with sustainability objectives while mitigating REs.

Furthermore, the conceptual maps and linked factors developed in this research offer policymakers a structured guide for identifying how REs may arise and which regulatory measures could minimize these undesired effects. The study also differentiates RE occurrences across micro-, meso-, and macro-levels, emphasising that policy interventions should not only address immediate operational efficiencies but also anticipate market-wide adjustments that may undermine sustainability goals.

Importantly, the research highlights the need for precise, long-term, and stable regulatory frameworks, especially in sectors like the automotive industry, to enable companies to effectively plan, implement, and monitor their CE practices. Robust monitoring and enforcement mechanisms are essential to ensure compliance and to avoid practices that could inadvertently generate REs.

Overall, this study provides a unified basis for managers and policymakers to understand, anticipate, and mitigate RE risks. It contributes actionable insights into potential trade-offs associated with CE initiatives, supports strategic planning, and offers a methodological foundation for future empirical research in industrial and B2B contexts. By linking CE strategies to specific rebound mechanisms and clarifying causal chains, the research equips both managers and policymakers with the frameworks needed to design more resilient circular strategies and more effective regulatory frameworks that avoid unintended rebound loops.

6. Conclusions

This thesis set out to address a significant and understudied challenge in the transition toward sustainable and circular industrial systems: the occurrence of REs during the implementation of circular strategies in manufacturing. While the CE seeks to decouple production growth from resource consumption and align industrial practices with broader sustainability objectives—including the SDGs—recent studies increasingly highlight that CE initiatives may unintentionally trigger REs, generating systemic responses that diminish or even reverse expected environmental benefits. Despite this concern, empirical evidence, methodological tools, and operational guidelines for detecting such unintended consequences remain scarce, particularly within manufacturing contexts where circular strategies are becoming central to long-term sustainability transitions.

To begin addressing this gap, the thesis undertook a comprehensive investigation of how CE and RE interact within manufacturing, with the dual objective of identifying where REs emerge and developing an operational tool to support companies in detecting their potential occurrence. Guided by the DRM, the research combined multiple theoretical and empirical stages. Through a series of systematic literature reviews, the study mapped the theoretical landscape of CE and RE across five key dimensions—Business model, Drivers, PLM, Circular manufacturing ecosystem, and Socio-economic aspects—thereby structuring the CE–RE domain and highlighting the factors and interdependencies that shape rebound behaviour. These reviews also exposed important knowledge gaps: a predominance of conceptual rather than empirical studies, fragmented and inconsistent terminology, limited understanding of RE mechanisms in industrial contexts, and the near absence of performance indicators to support RE detection within CE. In addition, the review of CE performance assessment methods revealed that while numerous tools exist to quantify circularity performance, they remain largely technocentric, focusing on material and energy indicators with limited capacity to detect unintended consequences. This further highlights the need for RE-aware assessment approaches and strengthens the rationale for the detection-driven tool developed in this work.

A major contribution of the research involved mapping circular manufacturing strategies—derived from Acerbi and Taisch (2020) and framed using the Circular Strategy Scanner—to the business processes where they are applied (business model, production, product design, procurement) and to the rebound mechanisms they may trigger. Thirty mechanisms were screened and selected across producer and consumer perspectives and linked to specific CE strategies. Illustrative examples were developed to show how efficiency improvements, cost reductions, behavioural shifts, or market adjustments could unintentionally generate additional resource use or emissions. This mapping advances theoretical understanding while laying the groundwork for practical identification of risk areas within industrial settings.

A critical insight from this work is that linking CE performance assessment methods to RE detection significantly enhances both theoretical understanding and practical applicability. By associating qualitative detection of potential REs with measurable indicators, such as resource efficiency, material flow changes, and product lifecycle outcomes, companies can monitor and respond to unintended consequences more effectively. This integration bridges the gap between conceptual frameworks and operational monitoring, supporting evidence-based decision-making, early warning, and proactive mitigation of REs.

The thesis further contributes to knowledge through the development of conceptual maps and the reference model. The conceptual maps were consolidated into a reference model that integrates the five CE–RE dimensions into a coherent structure, clarifying how specific cause–effect relations may trigger different types of REs—direct, indirect, economy-wide, and transformational—across micro, meso, and macro levels. This model provides a system-oriented understanding of how CE strategies, organisational decisions, consumer behaviours, and broader drivers interact to create rebound pathways. Importantly, insights from the CE performance assessment literature demonstrate that current measurement tools insufficiently represent these interactions. The absence of integrated, cross-process indicators capable of capturing RE dynamics reinforces the value of developing system-based models and detection tools capable of addressing these overlooked aspects. Building on this, the reference model was transformed into an impact model, offering a more actionable representation of dynamic relationships. The impact model introduces additional factors, causal links, and intervention points, and positions the detection tool within the broader system, showing where its application is most effective in supporting early identification and prevention of REs.

Empirical insights obtained through interviews further revealed a generally low level of awareness regarding REs within CE implementation, while simultaneously highlighting a growing recognition of alternative negative consequences associated with circular transitions. These findings reinforced the need for a practical detection tool that could raise awareness, initiate internal discussion, and support informed decision-making.

The culmination of this research is the development of a detection-driven tool that supports companies in identifying potential REs during the implementation of circular strategies. Integrating CE strategies, sustainability objectives, SDGs, mapped rebound mechanisms, and relevant performance indicators, the tool provides a structured, user-friendly questionnaire that helps practitioners recognise where and how unintended effects could emerge. Its design—integrating structural and behavioural diagnostic questions—encourages reflection on organisational practices, decision-making processes, operational changes, and contextual factors that may trigger rebound pathways. Rather than quantifying REs, the tool identifies which mechanisms are potentially active and highlights the variables and indicators that should be monitored to detect early signals of rebound behaviour, thereby operationalising a research domain that has traditionally remained theoretical.

The detection-driven tool was validated through expert interviews with academics specialising in CE and industrial practitioners working in sustainability roles. Experts confirmed its novelty, usefulness, validity, and timeliness, highlighting the lack of comparable instruments capable of helping companies anticipate and detect REs within circular manufacturing. Their feedback led to substantial improvements, including clearer definitions, refined questionnaire items, enhanced navigation, stronger coherence across spreadsheets, easier access to supporting information, and a clearer, more interpretable results section.

Importantly, the validation process also reinforced the tool's applicability in real-world contexts, particularly within sustainability projects that integrate circular strategies. It demonstrated the tool's practical value for organisations

seeking to maximise the sustainable benefits of their initiatives by proactively managing and mitigating potential REs.
This is especially relevant given that firms currently rely heavily on LCA-based KPIs and resource-efficiency indicators, which, as highlighted in the CE performance assessment review, are not designed to detect rebound-related risks. The tool therefore complements existing assessment practices by introducing a structured way to account for unintended effects.

The research also has limitations. It focuses primarily on manufacturing and does not include other industrial sectors where rebound pathways may differ substantially. Several components of the conceptual maps are based on earlier CE–RE studies and therefore do not reflect the most recent scientific advances, as they were developed during the preliminary stages of this work. Moreover, the mapping between CE strategies and rebound mechanisms remains theoretical and is illustrated through hypothetical examples rather than real cases.
A further limitation concerns the detection-driven tool developed in this thesis. Although it represents a structured attempt to operationalise the identification of REs in circular manufacturing, it has not yet been applied in real industrial environments. Its validation relied on a modest number of expert interviews, only three of which involved industrial practitioners, and all from the same company, while the remaining participants were academics. The interviews provided valuable insights and contributed to refining the prototype; however, the predominance of academic perspectives means that the evaluation does not fully capture the diversity of operational constraints, decision-making routines, and practical challenges encountered across different industrial settings. A broader validation involving additional industrial experts, ideally from multiple sectors and company sizes, would therefore be necessary to more robustly assess the tool's practical relevance, applicability, and usability in real manufacturing contexts. Strengthening this phase would not only increase confidence in the tool's effectiveness but also provide more nuanced feedback to guide future refinements. As it stands, the tool's effectiveness, usability, clarity, and practical relevance for practitioners remain only partially verified. In the absence of concrete application cases, it is not yet possible to determine the extent to which the tool supports decision-making, whether companies interpret the questions as intended, or how it performs under real organisational constraints, data-availability limitations, and operational complexities.
In addition, the detection tool is qualitative in nature and generates indicative rather than quantitative results. Its implementation in an MS Excel-based format, while advantageous for accessibility and ease of use, also introduces functional limitations. The spreadsheets lack advanced features such as automated completeness checks, interactive navigation, dynamic prioritisation of risks, and integrated dashboards for monitoring CE indicators. Although the choice of Excel is justified by its ubiquity and low entry barrier, a brief exploration of alternative software implementations, such as web-based interfaces, dedicated assessment platforms, or modular decision-support systems, could offer additional perspectives on how the tool might evolve to enhance functionality, user engagement, and scalability.
Finally, the absence of robust and widely accepted performance indicators for detecting rebound effects in CE remains a significant methodological constraint. This limits the possibility of grounding the tool in established

metrics and underscores the need for future research aimed at developing, standardising, and validating indicators capable of supporting more rigorous, systematic, and potentially quantitative rebound detection.

In conclusion, this thesis provides both conceptual insight and practical support for detecting, recognising, and understanding the potential occurrence of REs within circular manufacturing. The integrated models, mappings, and detection tool developed herein represent meaningful advances toward more resilient and informed circular transitions. By helping companies anticipate potential unintended consequences early in their CE journey, this research contributes to strengthening the effectiveness, transparency, and long-term sustainability of circular strategies—laying a robust foundation for a circular future that avoids replicating the pitfalls of the linear past.

7. Future works

The limitations identified in this research highlight several promising directions for future development. While the current MS Excel-based tool provides an important proof of concept, its functionalities remain limited by the platform's constraints in terms of interaction, automated validation, and dynamic data processing. A natural next step is the development of a fully digital, interactive version, such as a web-based platform or integrated decision-support module, that would enable automated completeness checks, adaptive guidance, dynamic risk visualisation, and seamless integration with company data systems. Such a version would greatly enhance usability, accessibility, and the tool's capacity to support practitioners in real operational contexts.

A central avenue for future research is the empirical validation of the tool in industrial environments. Deploying the tool in real companies through concrete application cases is essential not only to test its technical performance but also to deepen the understanding of its practical usability, interpretability, and relevance for different professional roles. Broader validation involving a larger and more diverse group of industrial experts, beyond the limited number consulted in this work, will be critical to fully assess the tool's applicability across manufacturing contexts. Future studies should therefore implement the tool across diverse industries, through case studies, pilot tests, field experiments, and practitioner workshops, to observe how users navigate its structure, how questions are interpreted, whether rebound mechanisms are effectively recognised, and which components require refinement.

Workshops should also be organised to capture the range of perspectives represented by different sustainability roles within companies and to explore how various types of projects may fall within the intended scope of the detection-driven tool. This empirical phase will be crucial for improving question wording, strengthening mechanism descriptions, refining indicator suggestions, identifying sector-specific contextual variables, and determining the level of guidance practitioners require. Ultimately, real-world applications will support the evolution of the detection-driven tool from a qualitative conceptual diagnostic framework into a robust, validated, and practitioner-oriented support system.

Future research should investigate behavioural aspects within companies, exploring how internal decision-makers may unintentionally trigger rebound mechanisms through cognitive biases and organisational dynamics. Studies could examine how managers and employees follow psychological patterns analogous to those observed in consumers, which may both facilitate circular economy adoption and increase the risk of rebound effects. For instance, managers might interpret the implementation of a single circular initiative as sufficient proof of environmental responsibility, thereby justifying more resource-intensive decisions elsewhere in the organisation—an organisational analogue of moral licensing. Additional behavioural factors, such as optimism bias, narrow framing, habitual decision-making, or a tendency to prioritise short-term efficiency over long-term systemic outcomes, may further distort perceptions of risks and benefits associated with CE strategies. Understanding these behavioural triggers will be crucial for developing targeted mitigation strategies, designing decision-support tools, and structuring organisational processes to minimise the likelihood of behaviourally induced REs.

The qualitative nature of the tool means that it currently identifies potential rebound mechanisms without quantifying their likelihood or magnitude. Future research should therefore focus on developing quantitative or hybrid approaches, supported by empirical datasets, to complement the qualitative assessment. This could include indicator-based evaluation frameworks, early-warning thresholds, probabilistic estimates, or system-dynamics simulations capable of modelling long-term rebound trajectories. Such advancements would significantly enhance the tool's diagnostic precision and strategic value.
Another important avenue concerns sector-specific refinement. Designed for broad applicability across manufacturing, the tool could be strengthened through the development of industry-specific modules or tailored question sets reflecting the unique characteristics, technologies, material flows, and supply-chain structures of different sectors. This would enhance relevance and ensure that rebound mechanisms are contextualised according to distinct industrial realities. Future research should also explore differences across industries more systematically identifying which rebound pathways are sector-specific and how contextual variables (e.g., process type, value-chain configurations, regulatory environments) shape RE emergence.
Related to this, future works should also explore differences across industries more systematically, identifying which rebound pathways are sector-specific and how contextual variables (e.g., process type, value-chain configurations, regulatory environments) shape RE emergence. Related to this, there is substantial potential to deepen the analysis of enabling digital technologies, such as PLM systems, digital twins, Internet of Things infrastructures, and advanced analytics, and their role in detecting, predicting, or preventing REs. While this work highlights the relevance of PLM and data-driven approaches for structuring product-related and operational information, future studies should empirically investigate how such systems can evolve to better integrate CE-specific data models, dynamic circularity indicators, and early-warning signals related to REs. This includes examining how digital architectures might incorporate real-time data streams, artificial intelligence driven anomaly detection, or scenario analysis modules capable of identifying misalignments between circular strategies and actual system behaviour. Advancing this line of research would support the development of digitally enabled RE monitoring architectures, helping companies embed rebound considerations into daily decision-making routines and continuously track sustainability performance across the product lifecycle.
Beyond detection, future research should place increased emphasis on actionable mitigation strategies. While this thesis focuses on identifying potential REs, the next step is to develop clear, evidence-based interventions that companies can adopt to prevent, minimise, or avoid the occurrence of rebound phenomena. These mitigation strategies may involve design principles (e.g., durability trade-offs, modularity considerations), operational measures (e.g., production planning, maintenance regimes), behavioural interventions (e.g., user engagement, pricing models), or governance mechanisms (e.g., procurement policies, supply-chain coordination). Integrating these strategies into the tool—through actionable recommendations linked to each mechanism—would transform it from a diagnostic instrument into a proactive decision-support system.

From a theoretical perspective, further research should continue expanding and validating the five CE–RE dimensions identified in this thesis. Deeper empirical exploration of each dimension—including behavioural drivers, socio-economic dynamics, ecosystem interdependencies, and lifecycle interventions—would address the existing knowledge gaps highlighted in the literature review. Future studies should also extend analysis to actors beyond the focal firm—suppliers, service providers, consumers, and intermediaries—to better understand how rebound mechanisms propagate through broader industrial networks.

Methodological advancements should also focus on the integration of systems-thinking tools to support both the detection and prevention of REs. Approaches such as system dynamics modelling, feedback loop analysis, causal loop diagrams, and multi-criteria decision methods can help visualise the interactions between CE strategies, contextual variables, and rebound mechanisms across business processes. In particular, developing visual and systemic mappings of REs within circular manufacturing, through causal loop diagrams and other closed-loop representations, would make it possible to trace how circular initiatives may unintentionally trigger behavioural, operational, or market-driven rebound responses. These models would clarify feedback structures, highlight leverage points for intervention, and support both qualitative assessment and quantitative simulation. Furthermore, PSS should be used as concrete empirical examples to illustrate how REs materialise in practice, including shifts in user behaviour, increased service intensity, asset utilisation patterns, or unintended demand stimulation. PSS-based case studies would offer valuable real-world evidence of how rebound mechanisms propagate through circular manufacturing systems and contribute to the validation and refinement of the conceptual framework proposed in this work.

Finally, future research should focus on developing a comprehensive performance measurement system for monitoring the benefits of circular strategies while simultaneously detecting potential REs. Such a system could draw from domains where REs are traditionally measured—such as energy economics or transport—and integrate them with CE principles and circularity indicators to support robust, multi-dimensional evaluation aligned with the TBL.

Overall, this thesis establishes a foundational framework for understanding and detecting REs in circular manufacturing. Future work should build upon this foundation by expanding empirical evidence, enhancing methodological sophistication, integrating actionable mitigation strategies, and developing more advanced digital tools that equip companies to implement circular strategies responsibly, effectively, and without unintended consequences.

List of contributions

Some of the contents developed in this thesis have been published in peer-reviewed research articles, for which I am a co-author. Specifically, the journal and conference papers referenced and considered in this thesis correspond to those presented throughout the stages of the research methodology illustrated in Figure 1.

Journal papers:

- M. Ferrante, M. Vitti, F. Facchini, C. Sassanelli, 2024, *Mapping the relations between the circular economy rebound effects dimensions: A systematic literature review*, Journal of Cleaner Production 456, 142399, doi.org/10.1016/j.jclepro.2024.142399
- M. Ferrante, M. Vitti, C. Sassanelli, 2025, *The evolution of circular economy performance assessment: A systematic literature review,* Renewable and Sustainable Energy Reviews 217, 115757, doi.org/10.1016/j.rser.2025.115757
- M. Ferrante, C. Sassanelli, D.C. Pigosso, 2026, *Rebound Effects in Circular Manufacturing: Overview of Potential Rebound Mechanisms Activated by Circular Strategies Across Key Business Processes,* Business Strategy and the Environment, doi.org/10.1002/bse.70562
- M. Ferrante, E. Beducci, F. Acerbi, A. De Carolis, O. Benedettini, M. Taisch, C. Sassanelli, *Unveiling the circular economy rebound effect in product-service systems: types, triggers, and mitigation strategies,* Smart and Sustainable Manufacturing Systems

Conference papers:

- M. Ferrante, M. Vitti, S. Digiesi, C. Sassanelli, 2023, *Investigating the circular economy's rebound effect in manufacturing: a systematic literature review,* Proceedings of the Summer School Francesco Turco
- M. Ferrante, M. Vitti, F. Facchini, C. Sassanelli, 2024, *Investigating the Potential of Technologies in Circular Economy's Rebound Effect Dimensions,* International Conference on Interoperability for Enterprise Systems and Applications, doi.org/10.1007/978-3-031-93995-2_16
- M. Ferrante, M. Vitti, F. Facchini, C. Sassanelli, 2024, *Circular Economy Rebound Effect: Theoretical Implications and a Research Agenda,* IFIP International Conference on Product Lifecycle Management, doi.org/10.1007/978-3-031-93319-6_1
- M Ferrante, M Vitti, G Mossa, C Sassanelli, 2024, *Assessing rebound effects in circular economy: insights from the automotive industry*, Proceedings of the Summer School Francesco Turco
- M. Vitti, M. Ferrante, G. Mossa, S. Digiesi, C. Sassanelli, 2025, *Life Cycle Assessment Of Production And Assembly Lines: A Research Agenda,* Proceedings of the Conference on Production Systems and Logistics: CPSL 2025. Offenburg: publish-Ing.
- M. Ferrante, M. Vitti, C. Sassanelli, 2025, *Indexes for assessing Circular Economy performance in industry: a systematic literature review*, COPERMAN

- M. Ferrante, M. Fernandes Aguilar, J. Mascarenhas, C. Sassanelli, 2025, *Exploring the rebound effect in product-service systems: towards a research agenda,* IJCIEOM
- M Ferrante, M Vitti, G Mossa, C Sassanelli, 2025, *Developing the reference model to decode the occurrence of Rebound Effect of Circular Economy,* IJCIEOM
- M Ferrante, M Vitti, G Mossa, C Sassanelli, 2025, *Detailing the Circular Economy Rebound Effect reference model through Rebound Effect mechanisms,* IFIP International Conference on Product Lifecycle Management
- M. Ferrante, M. Vitti, F. Acerbi, S. Digiesi, C. Sassanelli, 2025, *Exploring the Pairing of Circular Manufacturing Data Categories and Rebound Effect Factors,* IFIP Advances in Information and Communication Technology, doi.org/10.1007/978-3-032-03534-9_38
- M Ferrante, M Vitti, G Mossa, C Sassanelli, 2025, U*nveiling the gaps in circular economy performance assessment: a research agenda*, Proceedings of the Summer School Francesco Turco

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