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Edited by Juliano B. Araujo, Henning Hinderer, Tobias Viere, and Jörg Woidasky

Applied Circular Economy Engineering

Technologies and Business Solutions to Implement Circularity

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Contents

Preface

In an era marked by unprecedented environmental challenges and resource constraints, the concept of a circular economy (CE) has emerged as a pivotal framework for fostering sustainability and resilience across industries. *Applied Circular Economy Engineering* delves deeply into the multifaceted dimensions of CE, offering readers an academically rigorous yet practically grounded exploration of its principles, methodologies, and applications. This multidisciplinary endeavor seeks to illuminate the challenges and opportunities associated with CE implementation across key industries and domains.

The chapters within are organized into six comprehensive parts, each focusing on a crucial aspect of CE engineering and management:

- *Part 1* sets the stage with an introduction to CE, highlighting its challenges and proposing pathways for integrating CE principles into business and engineering practices. This section serves as a gateway to the diverse and rich discussions presented throughout the book.
- *Part 2* delves into the critical role of materials in CE. From the complexities of recycling aluminum alloys to the potential of polymer circularity, these chapters examine innovative approaches and technological advancements required to overcome barriers to material reuse and recycling. The insights offered are both practical and forward-looking, addressing current challenges while envisioning a sustainable future.
- *Part 3* shifts the focus to products, emphasizing design and servitization. Discussions range from the implementation of circular processes in industrial sectors like electric drives to the integration of circularity in healthcare and product design. These chapters underscore the importance of embedding circular principles during product development, offering case studies and methodologies that bridge theory and practice.
- *Part 4* explores the technological foundations essential for enabling CE processes. From advanced sorting technologies for polymers to digital innovations that optimize material flows, this section illustrates how emerging technologies can drive systemic change and facilitate the realization of CE goals.
- *Part 5* focuses on management and organizational strategies, addressing the implementation of circular business models, and resource efficiency management in small and medium-sized enterprises (SMEs). By combining

theoretical frameworks with practical applications, these chapters provide valuable insights into the integration of sustainability-oriented innovations within organizational structures.

- *Part 6* first contextualizes the cultural dimensions of CE engineering, followed by an exploration of the broader implications and limitations of CE. Adopting a critical lens, it examines the thermodynamic boundaries of circularity and the need for comprehensive indicators to assess its alignment with overarching sustainability objectives.

This book represents the culmination of contributions from experts across academia and industry, each bringing a unique perspective to the challenges and opportunities inherent in CE engineering and management. It is intended to serve as both a scholarly reference and a practical guide for professionals, researchers, and policymakers committed to advancing sustainable development through innovative circular practices. By bridging the gap between academia and industry, this book provides valuable insights for engineers, managers, policymakers, and researchers dedicated to fostering sustainability.

We extend our deepest gratitude to the contributors, whose expertise and perspectives have greatly enriched this work. We hope this book inspires innovation, fosters collaboration, and contributes to the realization of a more sustainable and circular future.

The Editors

About the Companion Website

This book is accompanied by a companion website.

https://www.wiley.com/go/circulareconomyengineering

This website includes:

- Circularity Indicator Toolkit

Part I

Introduction

1

Challenges and Perspectives of Applying Circular Economy in Business and Engineering

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1.1 Introduction

There is a trend among companies to shift toward the circular model of production, seeking to replace the old linear model of "take-make-use-dispose." The previous model relied on and still relies heavily on cheap energy, abundant minerals, materials, and credit (Webster 2017). Additionally, the environmental and social side effects mount to unsustainable levels, driving new government regulations and initiatives that focus on controlling and reversing the current scenario, e.g., the European Union (EU) Circular Economy Action Plan (European Commission 2020) or the US Save our Seas 2.0 Act (US Government 2020). This has led to a sense of urgency in companies, as they look to the circular economy (CE) as a way to mitigate the risk of mounting costs, shortages, and even the collapse of the system in the future.

In a wide array of definitions for CE, the following definition by the Ellen MacArthur Foundation (2013, p. 7) is the most prominent one: "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." While this definition highlights the crucial role of innovative business models, it overlooks the broader systemic transformation required for a successful transition to a CE. To incorporate this as well, Kirchherr et al. (2017, p. 224) define CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish

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sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. It is enabled by novel business models and more responsible consumers."

Ultimately, CE offers companies the opportunity to simultaneously comply with increasingly stringent environmental regulations while achieving favorable economic outcomes. As highlighted by Geissdoerfer et al. (2018) and Padilla-Rivera et al. (2020), CE can significantly improve organizational environmental practices and contribute to broader sustainability goals.

Some countries have embraced CE principles sooner and implemented policies and legislation to support them. Germany was a pioneer in integrating CE into laws as early as 1996 (Barreiro-Gen and Lozano 2020). Japan and China followed in the next decade launching national laws related to CE (Geissdoerfer et al. 2017). The Netherlands subsequently launched its own CE program to increase its readiness for circularity across various industries. Supranational bodies have also incorporated CE concerns, most notably the EU. The European Commission (2020, p. 2) asserts that the CE "will play a pivotal role in achieving climate neutrality by 2050 and decoupling economic growth from resource consumption, while ensuring the EU's long-term competitiveness and promoting social inclusivity." Nevertheless, the world is still at an early stage of implementing CE, with only 7.2% of the global economy being circular in 2023, as described in the Circularity Gap Report (Circle Economy 2023).

Companies are seeking guidance on how to implement CE practices throughout their operations, and they require practical advice to make circularity operational. This support is needed at all hierarchical levels: strategic, tactical, and operational (Barreiro-Gen and Lozano 2020). Thus, the transition to a CE relies on a systemic and coordinated approach that spans strategic to operational aspects.

This chapter aims to present a comprehensive framework for effective CE implementation. It will provide an overview of corporate circularity adoption levels, as assessed through circularity maturity assessments. Additionally, it will explore the pivotal role of circular innovations as the key step in circular economy engineering (CEE) that drives CE implementation.

The first section covers both the top-down and bottom-up perspectives on CE implementation. This chapter then introduces the concept of a CE Readiness Assessment tool, which can help organizations gain greater awareness and leadership support for CE implementation. Finally, this chapter delves into the connection between CE and eco-innovation.

1.2 Strategic Approach for CE Implementation

The CE implementation must consider its systemic nature and work according to four hierarchy levels, namely the nano, micro, meso, and macro perspectives (Kirchherr et al. 2017; Saidani et al. 2017). From a macro perspective, the focus is on the global or national level, emphasizing entire industries. At the meso level, attention shifts to the regional scale, with a focus on business arrangements such as eco-industrial parks. Moving to the micro level, the focus is on the company value chain. Finally, the nano level concentrates on the circularity of products, components, and materials, which need to be designed or applied in a way that allows circular usage and avoids disposal at the end of a product's lifecycle.

According to Lieder and Rashid (2016), CE implementation on a large scale must happen in an integrated manner, considering both a top-down approach from public institutions and a bottom-up approach through businesses. In this way, the two sides act in a way that converges their interests, i.e., the environmental benefits of public institutions and the economic growth and prosperity of businesses. The interaction between both generates a dynamic of forces that can guarantee or prevent the CE implementation. Figure 1.1 illustrates the two-way approach necessary for CE implementation.

At the company level, to successfully shift toward a CE, it is important to implement material flow strategies such as reducing resource consumption, extending resource use periods, and recovering resources at the end of their lifecycle. It is also necessary to design circular products, which means that, already during the engineering process of a new product, the further usage of parts or materials in a circular manner must be a guiding design principle. Baldassarre et al. (2019) provide a focus on other key CE ingredients, namely, technical innovation, new business models, and collaboration. In this regard, circular business models (CBMs)

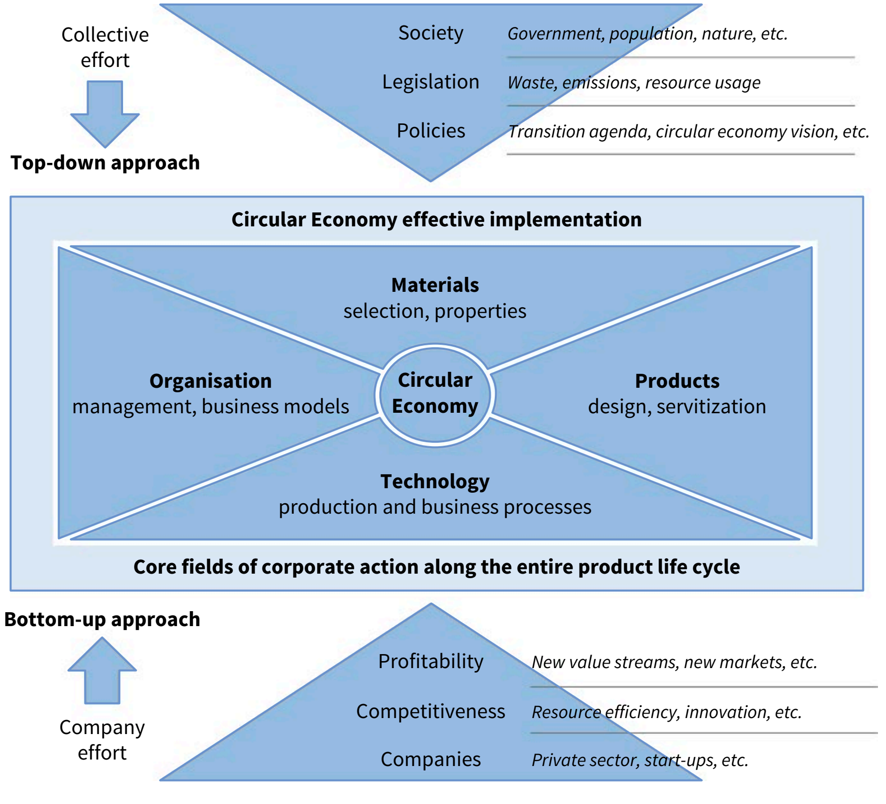

Figure 1.1 Top-down and bottom-up approaches for circular economy implementation. *Source*: Adapted from Lieder and Rashid (2016).

play a pivotal role in implementing CE at the organizational and management levels, as they simultaneously align corporate economic objectives with broader circular and sustainability goals. As noted by Lüdeke-Freund et al. (2019), CBMs create value for companies, customers, the environment, and society, offering benefits such as cost savings and the reduction of adverse ecological and social impacts. Among the numerous types of CBMs, product–service systems (PSS) represent a notable example, where a combination of products and services is utilized to meet customer needs without necessarily requiring the consumer to have ownership of the physical product. As per Montag and Pettau (2022), PSS can catalyze a change in production and consumption patterns, leading to a transition away from material-intensive products toward more dematerialized services.

Thus, the adoption of CE requires advancements in product development practices with multiple life cycles in mind. Over the past decade, considerations related to circular product development and engineering have emerged as a prominent focus in CE research (Reslan et al. 2022). A key guiding principle in ecodesign is the waste hierarchy, as outlined in the European Waste Framework Directive (European Commission 2022). This hierarchy establishes a priority order for waste management, favoring waste prevention as the most preferred option, followed by reuse, recycling, other forms of recovery (e.g., energy recovery), and, finally, disposal, which is the least preferred option (den Hollander et al. 2017). There are various strategies for ecodesign, depending on the objectives and phase of the product development process. These strategies encompass approaches such as design for recycling, design for reuse, and design for disassembly, among others, collectively referred to as Design for X (DfX).

A key implication of CE for corporate production processes is the necessity for improved control and monitoring of manufacturing activities, specifically through the integration of metrics related to natural resources and environmental flows. Industry 4.0 technologies can play a pivotal role in this endeavor by enhancing material efficiency and minimizing production waste. These technologies facilitate a comprehensive approach that considers various stages of the product lifecycle and fosters better information and resource exchange across the supply chain (Eisenreich et al. 2022). An integrative illustration of the essential components for implementing the CE can be seen in Figure 1.1.

At the company level, guides and standards for CE implementation contribute to enhancing circularity comprehensively across the value chain. These guides and standards provide direction on concepts, strategies, practices, and indicators (Barreiro-Gen and Lozano 2020; Pauliuk 2018; Reslan et al. 2022). They are designed to harmonize the understanding of CE and to support its implementation and measurement. According to Pauliuk (2018), some advantages of using guides and standards by companies include detailed CE definitions, detailed CE implementation frameworks, a CE systemic integration approach, and a database containing concrete business cases of companies following CE implementation. Notable examples of such standards include BS 8001:2017, introduced in the United Kingdom, and the ISO 59000 family of standards, recently released by the International Organization for Standardization (ISO).

Another critical factor for the successful implementation of CE practices in companies is the elucidation of their economic advantages, a topic that remains inadequately addressed in the current literature. While existing research predominantly focuses on aspects such as waste management, resource utilization, and environmental impact, this focus is somewhat narrow and often fails to address the specific economic benefits that CE can provide to companies. Lieder and Rashid (2016) emphasize that merely establishing closed-loop supply chains is insufficient. Companies must also determine how to generate value through these supply chains. Therefore, a more nuanced understanding of how CE can enhance economic performance is essential for companies seeking to implement these practices effectively and sustainably. Economic advantages might derive, e.g., from a better access to materials or resources since these stay within the closed-loop supply chain, by tapping into new and attractive market segments, or from an early preparation for increasingly strict statutory regulations.

Companies should also address the roles of critical stakeholders during CE implementation. It requires the contribution and commitment of the entire organization and the conscious management of stakeholders. According to Bjørnbet et al. (2021, p. 11), "CE does not have one product or one actor as a point of departure. (...) This implies that CE implementation in manufacturing companies cannot be done in one department or even one facility. It requires contribution and commitment from the entire organization and conscious management of stakeholders."

1.3 Comprehensive Evaluation of Business Circularity Readiness

Even with companies growing interest in becoming circular, the migration from a linear economy to CE has proven to be intricate. According to Tan et al. (2022), the lack of technical knowledge and expertise in CE and CEE is a serious roadblock for companies and their leaders. For example, businesses do not dominate pivotal issues like material flow, circular strategies, and new product design. Consequently, companies end up following strategies not aligned with CE principles.

In this knowledge-missing context, a CE readiness assessment can provide a snapshot of the current situation and highlight critical actions for its progress. It can play two relevant roles: to assess the current CE maturity level and to engage company leadership by informing and raising awareness over CE principles. "The maturity models provide scaffolding in the form of presentation of a desired evolution path from which organizations can define reasonable and desirable plans for engagement with the CE" (Uhrenholt et al. 2022, p. 1).

CE readiness assessment tools offer scores to different components of the company value chain, such as supply chain, strategy, operations, technology, and human resources (HR). Moreover, the tool can offer a business a systemic view, integrating its different parts toward a single vision for CE progress. Recently, several tools have been released by academic authors and organizations. Examples of circularity assessment tools are Circulytics (Ellen MacArthur Foundation 2019), MATChE

(Pigosso and McAloone 2021), and the systemic perspective of Uhrenholt et al. (2022). While each of these methods has its own set of goals, scopes, strengths, and weaknesses, users can select the one that aligns best with their requirements.

For instance, Pigosso and McAloone (2021) introduced a comprehensive approach encompassing a total of 8 dimensions and 30 aspects suited to evaluate organizations. Nevertheless, this method is more suited to manufacturing companies and may not be as relevant to other industries. Alternatively, Ellen MacArthur Foundation's (2019) Circulytics measures 18 indicators across 11 themes, using a more quantitative approach that requires extensive data collection. A third model was proposed by Uhrenholt et al. (2022), which proposed six different maturity levels. Also, their approach is more concise and offers users greater autonomy in its implementation, but with less technical depth. In Figure 1.2, a shorter representation of the model proposed by Uhrenholt et al. (2022) is available. Resuming, CE maturity assessment tools break down the organization into its different organizational parts and serve as a subsidy for the preparation of a long-term transformation plan.

For the maturity assessment to be conducted, the tools provide a list of best practices that serve as a reference for comparison with the company's current situation. At the strategic level, companies must integrate CE into their approach and communicate their value proposition to customers. The involvement of senior management is important at this stage, as it is essential to support the transition from linear to CBMs (Eisenreich et al. 2022). At the organizational level, companies should integrate CE principles into their governance practices by establishing well-defined roles and routines while simultaneously promoting the development of innovative business models (Yriberry et al. 2023). Eisenreich et al. (2022) affirm that HR also play an important role in integrating CE within companies, as it encompasses the training of employees in systems thinking, environmental awareness, regulatory compliance, advanced technologies (e.g., Industry 4.0), and CE principles. It also fosters a corporate culture that prioritizes sustainability and employee well-being.

The circular product development as the key CEE function aims to extend product lifespans and promote a multi-life-cycle approach through reuse and sharing

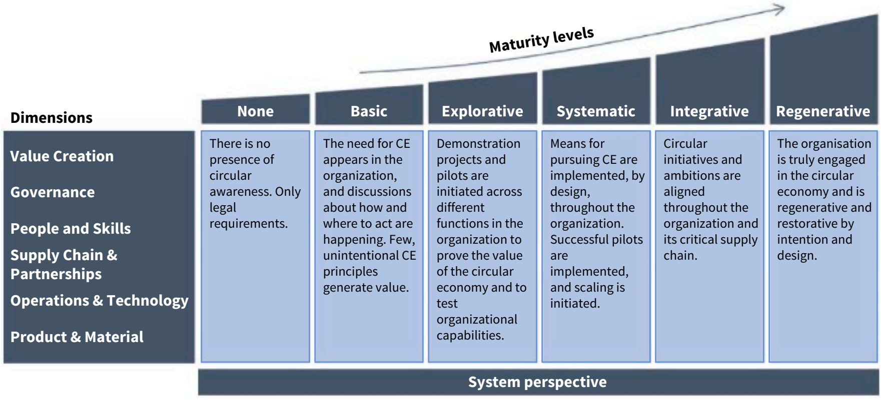

Figure 1.2 Example of circular economy maturity model. *Source*: Adapted from Uhrenholt et al. (2022).

strategies while also reducing environmental impacts across the entire product life cycle (Aguiar and Jugend 2022). Companies are increasingly focusing on developing PSS, incorporating designs that consider end-of-life management and promote sharing schemes. Within the supply chain, companies are increasingly integrating circular practices across various stages, including procurement, inbound logistics, operations, outbound logistics, reverse logistics, and recovery. Examples of best practices in this area include sourcing secondary materials, forging long-term partnerships with suppliers, and leveraging Industry 4.0 technologies (Uhrenholt et al. 2022). Innovation and emerging technologies also play a fundamental role in promoting circularity. It constitutes a strategic enabler of entire value-chain transformations, supporting other functions with solutions such as additive manufacturing, simulation, and biodegradable solutions (de Jesus and Mendonça 2018; Rosa et al. 2020).

1.4 Overview of Current Progress in Business Circularity

Various case studies on CE business readiness assessment have yielded previous results that indicate a low maturity level for most of the companies during their journey across CE implementation (Barreiro-Gen and Lozano 2020; Gusmerotti et al. 2019; Kalmykova et al. 2018). Based on the literature, they do not often have established systematic approaches for CE and have not successfully incorporated principles of CE into their operations, value chain, partnerships, and especially in their plans for generating regenerative and restorative value.

This issue also extends to countries considered frontrunners in CE. For instance, a CE report focused on the Netherlands (Hanemaaijer et al. 2023) emphasizes that there is no clear evidence of an accelerated transition toward a CE. According to the report, companies classified as circular (i.e., those implementing a circularity strategy as a business activity) constitute only 6% of all businesses in the country. Furthermore, the report highlights that the current economic system continues to impose substantial barriers, making genuinely CBMs insufficiently profitable at present. A key obstacle to advancing CE practices is the underdeveloped and, thus, inadequate market demand for circular products and services, which is influenced by factors such as financial costs, inconvenience, and entrenched social norms and habits. Another obstacle is the excessive focus of circular policies on low-value recycling, which provides little to no incentive for companies to adjust their current circularity strategies. Strategies targeting the reduction of new raw material consumption or the extension of product lifespans continue to receive comparatively insufficient attention.

Gusmerotti et al. (2019) conducted a study involving 821 firms in Italy through a questionnaire-based survey. The findings indicate that CE internalization is still at an embryonic stage, with only one-third of the surveyed companies beginning to change their routines and adopt CE principles in their processes. Among these firms, 10% emphasized resource efficiency to simultaneously reduce environmental impacts and costs, while 15% integrated CE at the design level, seeking competitive

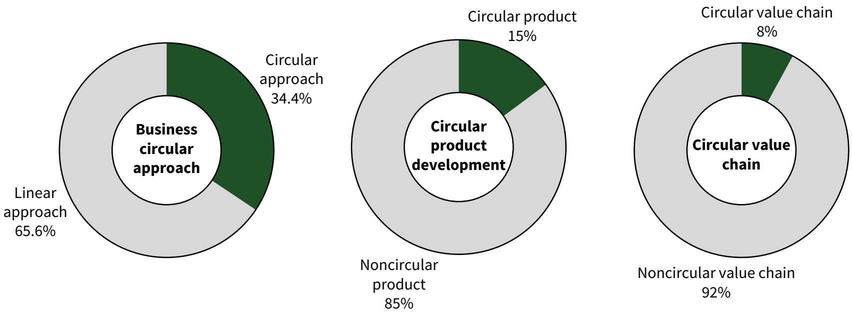

Figure 1.3 Case study on business circular maturity. *Source*: Adapted from Gusmerotti et al. (2019).

advantage by offering products with circular concepts. Notably, only 8% of the companies had genuinely introduced CE across all dimensions of their business. The results for this case study are presented in Figure 1.3.

Following, Barreiro-Gen and Lozano (2020) conducted a survey utilizing the Global Reporting Initiative (GRI) database to collect responses from companies regarding their preferences for different CE strategies. Their findings indicated that the adoption rates were higher in specific sectors, particularly those dealing with hazardous waste, packaging, critical materials, and food. The study also revealed that companies have placed greater emphasis on developing practices related to reducing and recycling, while less attention has been given to repairing and remanufacturing, which are the most desirable practices from a circularity maturity perspective.

A literature review conducted by Kalmykova et al. (2018) found that approximately 35% of companies are actively developing CE projects and have established a vision and planning for the topic. The study also identified that the stages of the value with the highest number of CE practice cases were "recycling and recovery" and "consumption and use," which together accounted for nearly 50% of all CE implementation cases. The prevalence of recycling over other CE strategies can be attributed to the historical emphasis placed by both companies and the public sector on waste management practices, rather than on restorative and regenerative approaches to materials. Finally, it has become evident that companies are primarily focused on internal actions rather than on external collaboration with stakeholders. It is important to recognize that organizations are not isolated entities and must collaborate with their stakeholders to achieve the objectives of CE and sustainability (Kalmykova et al. 2018).

1.5 Innovation as a Key Driver for Business Circularity

The successful implementation of CE practices within companies is significantly influenced by their capacity to foster both internal and collaborative innovation. Innovation, in its various forms, provides substantial ecological and economic benefits and is considered a crucial element in transitioning from linear to circular production and consumption systems (Jesus et al. 2018). As such, innovation plays a key role in enabling CE and CEE strategies, including the efficient use of materials, the extension of product and component lifespans, and advancements in product use and manufacturing (Kirchherr et al. 2017). Conversely, the adoption of CE presents a significant opportunity to drive innovation within businesses, thereby alleviating conflicts between economic and environmental objectives (Gusmerotti et al. 2019).

Existing literature identifies six primary dimensions of circular innovation: product development, production processes, business models, technological advancements, organizational models, and consumer engagement (Figure 1.4; de Jesus et al. 2016; Prieto-Sandoval et al. 2018; Suchek et al. 2021). These domains represent critical areas where companies must innovate to align with CE principles, fostering resource efficiency, waste minimization, and sustainable value creation.

The implementation of CE principles in product and service development fosters innovative design practices that prioritize maintaining product integrity over traditional end-of-life strategies. Grounded in the principle of inertia, CE mitigates obsolescence through resistance, delay, and reversal (den Hollander et al. 2017). As noted by the authors, circular product design encompasses innovative strategies to enhance product integrity and facilitate recycling, thereby preventing and reversing obsolescence at all levels of the product lifecycle. These strategies align with Potting et al.'s (2017) 10R framework, which includes refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover approaches. Chen and Rau (2023) also highlight the significant role of innovation in designing circular products. For instance, innovations in developing new components that are more symmetrical or easily identifiable can enhance product remanufacturing. Another example is the adoption of new manufacturing processes that avoid using coatings or spray paints, which can facilitate subsequent repair and maintenance.

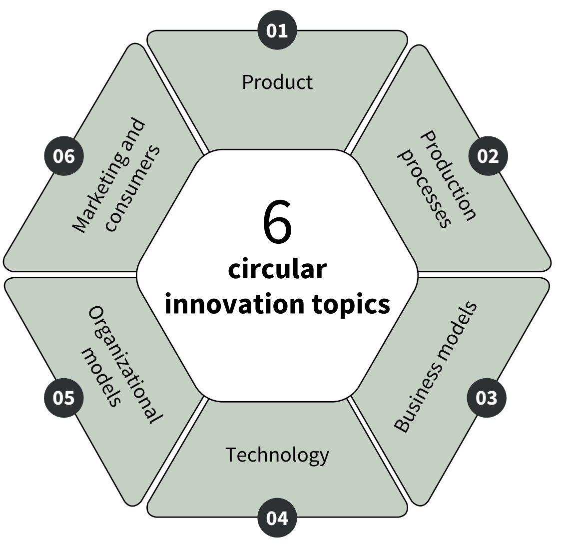

Figure 1.4 Relevant topics on the frontier between circular economy and innovation
Adapted from de Jesus et al. (2016); Prieto-Sandoval et al. (2018); Suchek et al. (2021).

Process-related innovation is moving toward improving efficiency. Avraamidou et al. (2020) assert that process intensification, a concept closely aligned with CE, is a notable phenomenon in the industry and an example of process-related innovation. Essentially, the aim of process intensification is to achieve ambitious production targets while significantly reducing the size of production equipment, energy consumption, and loss generation. Process-related innovation is generally framed by different authors into two broad categories: end-of-pipe and clean technologies. In both cases, environmental impacts are neutralized or minimized (Pichlak and Szromek 2022).

Incorporating business model innovation within CE can substantially enhance economic value while ensuring compliance with increasingly stringent environmental regulations. This approach enables businesses to create shared value aligned with CE principles. However, established firms often face greater challenges in transforming their existing business models compared to newly formed companies, which are typically more adaptable and open to disruptive innovations during the development of new business models (Gusmerotti et al. 2019; Suchek et al. 2021).

Companies must actively adopt innovative technologies capable of disrupting traditional practices and promoting circularity. As noted by de Jesus et al. (2016, p. 3009), "technological innovation is essential for enhancing resource efficiency, production, and waste minimization." A subset of these technologies, referred to as digital technologies or industry 4.0, has played a critical role in driving CE forward. For instance, blockchain technology demonstrated its ability to enhance various CE practices, including circular sourcing, thus contributing significantly to the promotion of circularity (Khan et al. 2021). Simultaneously, Parmentola et al. (2022) warn about the potential negative impacts of blockchain on the environment, advising users to consider both the positive and negative aspects, e.g., greater energy consumption. In other words, although the innovations brought about by digital technology have a positive impact on the CE, caution is also necessary to consider the potential environmental challenges that may arise from their adoption. Widely acknowledged digital technologies encompass big data and analytics, autonomous robotics and vehicles, additive manufacturing, simulation, augmented and virtual reality, horizontal and vertical system integration, the internet of things (IoT), cloud, fog, and edge computing, as well as blockchain and cybersecurity (Rosa et al. 2020).

The implementation of innovative organizational practices is the basis for enabling the widespread adoption of CE principles in business, as organizational structures and processes must evolve to effectively support and integrate strategies that drive the transition to CE. As Pichlak and Szromek (2022) suggest, these innovations are particularly critical in fostering circular supply chains and in the adoption of new management practices aimed at minimizing waste and mitigating environmental impacts.

Marketing and consumer communication are also relevant innovation areas in the context of CE. A key advantage of the circular approach, compared to traditional marketing and branding strategies, is that it not only focuses on communicating