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Scaling up circular ecosystems through product design practices: An integrative framework☆

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ABSTRACT

To turn the current take-make-dispose economy into a circular one, companies need to employ circular design practices that induce systemic change by scaling up circular ecosystems. However, the research streams of circular design practices and circular ecosystems have developed separately, leaving a gap to understanding how companies can scale up circular ecosystems through circular product design. To address this gap, we bridge two perspectives. We develop a research framework which interlinks circular product design with circular ecosystem scalability and employ it in an exploratory empirical analysis. The resulting integrative framework illustrates the role of circular product design in enabling circular ecosystem scalability. For scaling circular ecosystems, we identify circular product design practices aimed to extend product lifecycle and particularly design for modularity/standardization as key practices, and functional scalability as a key scalability feature. The findings provide one of the first attempts to identify the most effective ways to scale up circular ecosystems by design, and analyze the number of circular ecosystem scalability features each circular product design dimension enables. We advance the academic debate about systemic circularity by positing the enabling role of circular product design in achieving circular ecosystem scalability. Our insights provide practical guidelines for managers and policymakers seeking to scale circular businesses with an ecosystem approach.

1. Introduction

Circular Economy (CE) preserves resource value in a regenerative economic model (Bocken et al., 2016) that decouples resource consumption from demand growth and contributes to the decarbonization of our economy (Kjaer et al., 2019; Liu et al., 2024). Achieving a CE necessitates systemic change at multiple levels, ranging from products and companies to networks and ecosystems, and extending to the regional and national levels (Aarikka-Stenroos et al., 2022; Merli et al., 2018). Nevertheless, this systemic change is arduous and remains incomplete, as companies generally prioritize product design practices at the level of their internal operations (Centobelli et al., 2020; Kaipainen et al., 2022), rather than driving systemic change towards the CE at the ecosystem level (Fernández-Arribas et al., 2024; Marini et al., 2024; Santa-Maria et al., 2022). To spread the implementation of the CE across its manifold levels, this research merges two perspectives: circular product design and circular ecosystem scalability.

The first perspective, namely circular product design, involves practices for designing products according to CE principles (Bocken et al., 2016; Konietzko et al., 2020; Sassanelli et al., 2020), such as remanufacturing (Urbinati et al., 2020). Recently, circular product design has gained paramount importance in the transition towards the CE (Bocken et al., 2016), yet lacks a wider application in industry (Trigkas et al., 2020). The discourse on circular product design has undergone significant expansion since the seminal contribution by Bocken et al., (2016), who proposed several circular product design dimensions, such as slowing, narrowing, closing, regenerating and inform (Aguiar & Jugend, 2022; Konietzko et al., 2020). Circular product design represents the first phase of the circular product lifecycle. Although typically managed by different companies, subsequent lifecycle phases need to be jointly considered from a systemic perspective during the design phase to avoid mismatches and burden shifting

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throughout the product lifecycle (Kanda et al., 2021; Sgambaro et al., 2024b). Therefore, a range of circular design practices must be implemented from a systemic perspective (den Hollander et al., 2017) to coherently advance systemic circular flows of resources, energy, and materials and to avoid rebound effects (Aarikka-Stenroos et al., 2021; Vegter et al., 2023). Nevertheless, there has been a paucity of research in this field, with the role of circular design practices in achieving a systemic CE transition having received little exploration (see e.g., Han et al., 2023; Pruhs et al., 2024).

The second perspective, namely circular ecosystem scalability, has been overlooked by research focusing on scaling circular business models (Bocken & Antikainen, 2019; Frishammar et al., 2025; Zucchella & Previtali, 2019) and, just recently, start-ups (Han et al., 2023). Circular ecosystems refer to diverse independent yet interdependent actors that collectively generate an ecosystem outcome typified by the circular processes of recycling, reuse, and reduction (Aarikka-Stenroos et al., 2021). Research on circular ecosystems remains scattered and is emerging with a focus on theoretical frameworks (Gomes et al., 2023), benefits (Harala et al., 2023), and specific industrial sectors (Chirumalla et al., 2022). Few contributions (e.g., den Hollander et al., 2017; Densley Tingley et al., 2017) deal with the features that define circular ecosystem scalability, as its ability to grow, respond to increasing demand and production, and build the necessary resources, structures, and capabilities (Cerqueus & Delorme, 2023; Koren et al., 2017). This theoretical gap is surprising given that circular ecosystem scalability is recognized crucial for advancing systemic change in the economy and overcoming various barriers in the CE. For example, as circular ecosystems allow achieving coordination among actors and their activities to jointly implement CE principles (Aarikka-Stenroos et al., 2021; Kanda et al., 2021), they reduce risks and uncertainties from the inadequate scale of operations, limited funding opportunities and implementation of circular practices (Zucchella & Previtali, 2019).

Combining the two perspectives, we assume that circular product design may span from companies to their ecosystems in a systemic manner (Bocken et al., 2016; Nujen et al., 2023; Toth-Peter et al., 2023), creating conditions for effectively scaling up circular ecosystems. Rather than focusing exclusively on the production lifecycle phase that is managed by the company designing and/or manufacturing the product itself (Bocken et al., 2016), circular design practices may encompass and influence entire ecosystems in which companies are embedded (Bocken et al., 2016; Nujen et al., 2023; Toth-Peter et al., 2023). In the context of circular product design, it is imperative to consider the various companies involved and their respective objectives and activities throughout the lifecycle of the circular product. For instance, when a company designs a circular product, this product may invite other companies to develop related remanufacturing processes, fostering not only individual processes and activities at involved companies, but also interdependences and mutual benefits in scaling circular ecosystems. However, there remains a paucity of academic literature investigating the interplay between circular product design and the scalability of circular ecosystems, which we argue to be important for building a much-needed framework for the systemic transition towards the CE (see, e.g., Zucchella & Previtali, 2019). To improve understanding to how companies can drive the systemic CE transition, our objective is to investigate circular product design practices that enable scalability features of circular ecosystems. Bridging these previously distant two concepts and theoretical discussions, we ask: *which company-level circular product design practices enable the scalability of circular ecosystems?*

First, we leverage the mature research stream on circular product design, and we merge it with circular ecosystem scalability. This process results in the conceptualization of a novel research framework. Second, we integrate the framework with an exploratory empirical analysis. The findings provide one of the first attempts to identify the most effective ways to scale up circular ecosystems by design, and analyze the number of circular ecosystem scalability features each circular product design dimension enables. Our research has relevant implications for both scholars and managers. From an academic standpoint, our research posits the enabling role of product design to achieve the scalability of circular ecosystem with an integrative framework. From a managerial standpoint, we propose that both the integrated framework and the ranking of circular design dimensions could act as practical guidelines to achieve scalability for advancing the systemic transition towards the CE.

The remainder of this paper is organized as follows. Section 2 explains the narrative literature review used for identifying the key components of our novel research framework and presents the overall structure of the framework. Section 3 describes the methodology. Section 4 presents our novel integrative framework and proposes a ranking of the circular design dimensions. Section 5 discusses the results in relation to previous literature. Lastly, Section 6 draws conclusions and paves the way for future research.

2. Towards a novel framework for circular ecosystem scalability

The research framework is based on an extensive and purposively conducted narrative literature review, which is particularly suitable when merging different domains to transfer ideas and connect different subject areas (Fan et al., 2022). The narrative literature review methodology entails reviewing current literature starting with a small sample of articles, incrementally increasing through snowballing the article sample as the authors' understanding of the field increases till saturation is reached. This procedure was repeated three times in order to identify (i) circular product design practices; (ii) circular ecosystems, their scalability, definitions, and origins; and (iii) the key scalability features that can be transferred to the circular ecosystem domain, leveraging on the well-developed academic literature about scalability in the field of computer science research (Stampfl et al., 2013). In each iteration of the narrative literature review, a content analysis (Weber, 1990) was performed on the collected articles to triangulate and cluster information. As a result, our research framework was compiled based on circular product design practices, described in Section 2.1, and circular ecosystem scalability features, described in Section 2.2.2.

2.1. Circular product design practices

The CE aims to preserve the value of resources and extend the lifecycle of materials and products, with the ultimate objective of closing resource loops (Bocken et al., 2016; Ghisellini et al., 2016). In order to achieve these objectives, it is essential that CE principles are embedded in products and services as early as possible in their lifecycle (Nujen et al., 2023; Sgambaro et al., 2024b). Hence, considering CE principles in the very first phase of a product/service lifecycle, namely the design phase, is fundamental for the transition towards the CE (Bocken et al., 2016; Centobelli et al., 2020; Urbinati et al., 2017).

Circular product design practices are particularly relevant to companies operating in resource and production intense sectors to reduce their environmental impacts and contribute to their decarbonization (Taddei et al., 2022). The current literature identifies many circular product design practices, which can be categorized according to distinct dimensions. Gunasekara and colleagues (2023) consider CE principles and the management of waste and returns to describe the most relevant circular product design practices. CE principles are also considered by Uvarova and colleagues (2023), who extend the initial 3Rs (reduce, reuse, recycle) to 60 related principles (the 60Rs), and by Morseletto (2020), who describes design practices under the 10Rs lens. Chen and Rau (2023) describe circular product design practices from the point of view of forward and reverse operations. Sassanelli et al. (2020) take the perspective of design-for-X abilities, namely, the product performances addressed by each design practice. A consistent stream of literature classifies circular product design practices according to strategies that aim to recycle and reduce resources. Product integrity was the milestone taken as a reference by den Hollander and colleagues (2017) to classify circular product design practices into long use, extended use, and

recovery. The seminal contribution by Bocken and colleagues (2016) classified design strategies into slowing, closing, and narrowing. This initial classification has since been updated, with subsequent studies building upon and refining it.(see, e.g., Aguiar & Jugend, 2022; Konietzko et al., 2020; Lüdeke-Freund et al., 2019).

Synthesizing the work of these authors, circular product design practices can be classified into five different dimensions: narrow, slow, close, regenerate, and inform. We use these dimensions in our paper as they focus on preserving the value of resources embedded in the final products, thus clearly distinguishing circular from linear approaches. Table 1 describes the circular product design practices recurring in the current literature and classified according to six circular design dimensions. We ended up with six dimensions by splitting the 'slow' dimension of the five listed above in two: (i) slow – product life extension and (ii) slow – long-life products. Our purpose was to clearly distinguish between design practices aimed to extend products' lifecycle (that fall into the slow – product life extension dimension) and those aimed to design long-lasting products (that fall into the slow – long-life products dimension).

Table 1
Circular product design practices.

Circular design dimension	Circular product design practices	Description	Main references
Narrow	Design for light weight	Designing products by reducing the amount of materials needed or developing brand-new solutions with no or less material required while maintaining products' basic functionalities	(Aguiar & Jugend, 2022; Konietzko, Bocken, & Hultink, 2020; Morseletto, 2020; Uvarova, Atstaja, Volkova, Grasis, & Ozolina-Ozola, 2023)
Slow – product life extension	Design for disassembly/ reassembly	Designing products and their parts so that they can be easily disassembled and reassembled into new products	(Bocken et al., 2016; Chen & Rau, 2023; Gunasekara, Robb, & Zhang, 2023; Konietzko, Bocken, & Hultink, 2020; Lüdeke-Freund et al., 2019; Uvarova, Atstaja, Volkova, Grasis, & Ozolina-Ozola, 2023)
	Design for upgradability/ adaptability	Designing products whose performance and value can be easily improved over time, maintaining their usability into the future by making them adaptable to the changing needs of users	(Aguiar & Jugend, 2022; Bocken et al., 2016; den Hollander et al., 2017; Gunasekara et al., 2023; Konietzko et al., 2020; Lüdeke-Freund et al., 2019)
	Design for modularity/ standardization	Designing product parts and interfaces suitable to fit more items to prevent systemic obsolescence	(Bocken et al.. 2016; Chen & Rau, 2023; Konietzko, Bocken, & Hultink, 2020; Lüdeke-Freund et al., 2019; Morseletto, 2020; Wang et al., 2022)
	Design for repair/ maintenance	Designing products so that they can be easily repaired, and maintenance can be easily carried out by different actors in the circular ecosystem	(Aguiar & Jugend, 2022; Bocken et al., 2016; Chen & Rau, 2023; den Hollander et al., 2017; Konietzko et al., 2020; Lüdeke-Freund et al., 2019; Morseletto, 2020; Sassanelli et al., 2020)
Slow – long-life products	Design for emotional durability	Designing products that final users will like for a long time and so will have a feeling of emotional attachment to them	(Aguiar & Jugend, 2022; Bocken et al., 2016; den Hollander et al., 2017; Konietzko et al., 2020; Lüdeke-Freund et al., 2019)
	Design for physical durability	Designing products whose performance will not degrade in a short period. Products' components and raw materials should therefore be durable and long-lasting to guarantee stable	(Aguiar & Jugend, 2022; Bocken et al., 2016; den Hollander et al., 2017; Konietzko et al., 2020; Morseletto, 2020)

(*continued on next page*)

2.2. Circular ecosystems

2.2.1. Origins and definition of circular ecosystems

Rooted in and inspired by the natural sciences, ecosystems have become popular in management research (Aarikka-Stenroos & Ritala, 2017; Adner, 2017; Jacobides et al., 2018). Ecosystems are characterized by diversity and complexity that manifests through inherent interdependencies and co-evolution among the ecosystem actors, who come together to achieve an outcome greater than any single actor would achieve alone (Aarikka-Stenroos & Ritala, 2017; Adner, 2017). The desired outcomes vary from creating value from business (Adner, 2017), innovation (Thomas & Autio, 2020), entrepreneurial activities (Pizzi et al., 2022), and platforms (Blackburn et al., 2022) to, recently, addressing grand challenges through the CE (Patala et al., 2022; Ritala et al., 2023). In this research, we focus on circular ecosystems with a business orientation, namely, those in which the collectively pursued ecosystem outcome focuses on fulfilling a shared value proposition (Adner, 2017) that adheres to sustainability through CE principles (Aarikka-Stenroos et al., 2021).

When developing such an ecosystem, the actors' activities and relationships are in constant motion, often unclear, and co-evolve unpredictably (Gomes et al., 2018). Typically, circular ecosystem scale-up is initiated by a central company that promotes circular practices (Zucchella & Previtali, 2019) and engages existing and new partners and orchestrate their roles and complementary activities (Kaipainen et al., 2023; Ritala et al., 2023; Santa-Maria et al., 2022; Zucchella & Previtali, 2019). In contrast to linear business, a longer-term orientation, mutual trust (Brown et al., 2021), and a larger number of actors with changing interdependencies are expected when developing circular businesses (Aarikka-Stenroos et al., 2021; Bocken et al., 2016; Sgambaro et al., 2024a). Hence, circular ecosystem emergence is characterized by a high degree of uncertainty (Tsytsyna et al., 2023) and business challenges, such as the management of resources (Asgari & Asgari, 2021). Therefore, further research is critically needed to understand the features that define scaling up a circular ecosystem to achieve circular system-level goals (see, e.g., Köhler et al., 2022).

2.2.2. Scalability features of circular ecosystems

The concept of scalability is relatively broad in literature and can refer to several domains. Considering the management perspective to ecosystems, scalability is defined as the ability of a business ecosystem to grow and respond to increasing demand and production by having the necessary resources, structures, and capabilities (Cerqueus & Delorme, 2023; Koren et al., 2017). The concept of scalability, even when applied to business ecosystems (i.e., in the business and management literature), draws on an existing and well-developed stream of literature on this

Table 1 (*continued*)

Circular design dimension	Circular product design practices	Description	Main references
		performance over a long period	
Close	Design components, where appropriate, with one material	Designing product components with a single material so they can be easily recycled at the end of their useful life	(Aguiar & Jugend, 2022; Chen & Rau, 2023; Konietzko et al., 2020)
	Design with materials suitable for primary recycling	Designing products for primary recycling; that is, recycled products' material properties are equivalent to virgin material properties	(Aguiar & Jugend, 2022; Konietzko et al., 2020)
Regenerate	Design with non-toxic materials	Designing products without toxic materials, components, or resources	(Aguiar & Jugend, 2022; Chen & Rau, 2023; Konietzko et al., 2020; Uvarova et al., 2023)
	Design with renewable materials	Designing products with renewable materials, components, and resources	(Aguiar & Jugend, 2022; Konietzko, Bocken, & Hultink, 2020; Uvarova, Atstaja, Volkova, Grasis, & Ozolina-Ozola, 2023)
	Design with regenerated inputs	Designing products with materials, components, and resources regenerated from used products and components	(Aguiar & Jugend, 2022; Chen & Rau, 2023; Konietzko et al., 2020)
Inform	Design connected products	Designing products with embedded digital technologies, such as sensors, so products can send and receive data	(Aguiar & Jugend, 2022; Chen & Rau, 2023; Konietzko et al., 2020)

matter in the field of computer science (Stampfl et al., 2013), where the definition of scalability is far more developed (see, e.g., Brockhaus et al., 2019; Muthukannan et al., 2021; Stampfl et al., 2013).

We draw from the domain of computer science to identify the key scalability features that can be transferred to the domain of circular ecosystems. In our review, we exclude features that refer solely to software, hardware, and application characteristics (i.e., scalability referring to processors and memory elements, respectively). The reviewed scalability features (Bondi, 2000; Camacho et al., 2020; El-Rewini & Abd-El-Barr, 2005; Shivakumar, 2015; Wang, 2018) include (i) application scalability (the ability of a system to run a software application with improved performance); (ii) functionality scalability (the ability of a system to add new functionalities without its performance being heavily affected); (iii) generation scalability (the ability of a system to update a hardware or software system by using next-generation components); (iv) geographic scalability (the ability of a system to satisfy additional geographic areas without heavily affecting its performance); (v) heterogeneous scalability (the ability of a system to use hardware and software components supplied by different vendors); (vi) integration scalability (the ability of a system to integrate new interfaces while continuing to operate within tolerable ranges); (vii) load scalability (the ability of a system to operate with a higher or lower workload without heavily affecting its performance); (viii) size scalability (feature measuring 'the maximum number of processors a system can accommodate' (El-Rewini & Abd-El-Barr, 2005); (ix) space scalability (the ability of a system to increase its memory as the number of elements it supports increases); (x) space–time scalability (the ability of a system to guarantee good performances as the items it encompasses grow by orders of magnitude); and (xi) structural scalability (the ability of a system to expand into a chosen variable without substantial changes to its architecture).

These reviewed scalability features can be synthesized into the following categories: (i) integration, functional, and structural scalability, that refer to the ability of a system to provide additional functionalities while guaranteeing the same performance; (ii) application and generation scalability, that refer to the ability of a system to have an upgraded and improved version of the system by integrating new components; and (iii) load and space–time scalability, that refer to the ability of a system to guarantee the same performance under changed operational conditions. Besides, (iv) geographic and (v) heterogeneous scalability refer to specific concepts (i.e., geographic areas and suppliers, respectively) and were therefore considered standalone categories.

As a result, we identify five scalability features applicable to achieve the scalability of circular ecosystems. Table 2 describes the scalability features and their application to circular ecosystems.

2.3. Research framework

As circular design practices involve the ecosystems in which a company operates (Bocken et al., 2016; Nujen et al., 2023; Toth-Peter

Table 2
Circular ecosystem scalability features.

Scalability feature	*Description*	*Main references*
Functional	A circular ecosystem's ability to adapt to the ever-changing competitive arena by applying further circular managerial practices whenever needed without compromising the ability to fully apply the CE managerial practices already in place or the ability to meet demand	(Morseletto, 2020; Ranta et al., 2018; Urbinati et al., 2017)
Generation	A circular ecosystem's ability to manage flows of new/innovative materials without compromising (or enhancing) the final product characteristics; this ability is critical to prolong as much as possible both resources and a product's useful life (e.g., by integrating new/innovative materials into remanufactured products)	(Copani & Behnam, 2020; Khan et al., 2020; Pialot et al., 2017)
Geographic	A circular ecosystem's ability to expand from a local to a larger geographic area by encompassing different actors based in different geographic areas that can manage the flow of resources, raw materials, and new and used products across different geographic areas and satisfy demand in multiple geographic areas	(Chertow, 2000; Domenech et al., 2019; Herczeg et al., 2018)
Heterogeneous	A circular ecosystem's ability to adapt efficiently and manage resources/raw material flows that come from different suppliers; this ability is critical to meeting fast-increasing demand and coping with supply shortages and geopolitical crises	(Meglin et al., 2022; Rogetzer et al., 2019)
Load	A circular ecosystem's ability to efficiently accommodate variations in resource/raw material flows and demand fluctuations without negative effects on its performance	(Densley Tingley et al., 2017; Kurilova-Palisaitiene et al., 2018)

et al., 2023), they may also influence the role that each company plays within the circular ecosystem (Aarikka-Stenroos et al., 2022). Consequently, we argue that these practices also enable ecosystems to scale up by creating the conditions for the effective implementation of scalability features. We developed a research framework to shed light on which characteristics of a circular ecosystem and the associated circular design practices of companies within it, create the conditions for scalability. Our novel research framework interlinks the circular product design practices with the circular ecosystem scalability features, as depicted in Fig. 1.

The narrative literature reviews allow us to (i) identify the two key components – circular product design practices and circular ecosystem scalability features – and thus (ii) to conceptualize our novel research framework that combines these two key components. The subsequent stage of the research involves integrating the aforementioned framework with empirical evidence in order to identify the matches between circular product design practices and circular ecosystem scalability features.

3. Empirical research methodology

3.1. Research design

To integrate our conceptualized research framework with empirical evidence, we deployed a multiple-case study methodology (Eisenhardt, 1989) and followed theoretical sampling (Eisenhardt & Graebner, 2007). We decided to focus on case studies representing company-centric circular ecosystems with large focal companies at a later stage of CE development (i.e., a pioneering attitude towards circularity manifesting, for example, through an industrial-scale CE business and active participation in CE research projects). This is because we assumed that such companies possess the necessary resources and propensity for scaling up their circular ecosystems, thus serving as a benchmark for small and medium-sized companies seeking to scale up their smaller circular ecosystems. The case sampling was based on the following inclusion criteria: (i) the company's role in the circular ecosystem is focal and pivotal for all the actors belonging to that ecosystem (i.e., the company acts as the connection point among a heterogeneous set of actors belonging to the circular ecosystem and compels them to follow its circular value proposition), and (ii) the focal company of the ecosystem has already applied CE practices focused on circular product design.

To identify potential cases, the Ellen MacArthur Foundation network and case studies website was utilized. We excluded case studies for which secondary data sources provided ineffective descriptions, thereby hindering a clear understanding of their CE practices (in accordance with previous articles, see, e.g., Modgil et al., 2021; Urbinati et al., 2017). Given the aforementioned exclusion and inclusion criteria, we selected and analyzed five case studies of company-centric circular ecosystems.

3.2. Research context

As illustrated in Table 3, the context of each selected case study is divided into two parts: (i) circular ecosystem and (ii) focal company. The first part concerns contextual information about the industrial sector and the involvement of new actors in the circular ecosystems with respect to the previous linear ecosystem. The second part concerns contextual information about employees and revenues of the focal company of the circular ecosystem. Besides, A brief description of the case studies is presented in Table 4.

3.3. Data collection

We collected case-specific information from the Ellen MacArthur Foundation network and case studies website and expanded it with distinct secondary data sources, including company websites, sectorial reports, magazines, and press releases. In addition, we have utilized professional databases, such as LexisNexis, to gather relevant information concerning our case studies and form a comprehensive perspective on their CE initiatives and activities. The utilization of secondary data was instrumental in facilitating data triangulation, thereby enabling the collection of richer nuances to capture the main CE activities, objectives and results concerning both circular product design and the benefits achieved through it, such as the scalability of the circular ecosystem. Given the exploratory nature of the case studies and the structure of business-oriented circular ecosystems, document-based data focusing on focal companies was deemed suitable and sufficient to reach data saturation (in accordance with previous articles, see, e.g., Modgil et al., 2021; Urbinati et al., 2017).

3.4. Data analysis

Employing an abductive analysis approach, we utilized the literature-based research framework (Fig. 1) for analyzing our empirical data to identify the matches interlinking circular product design practices with circular ecosystem scalability. This approach allows to develop novel concepts through a combination of theoretical insights,

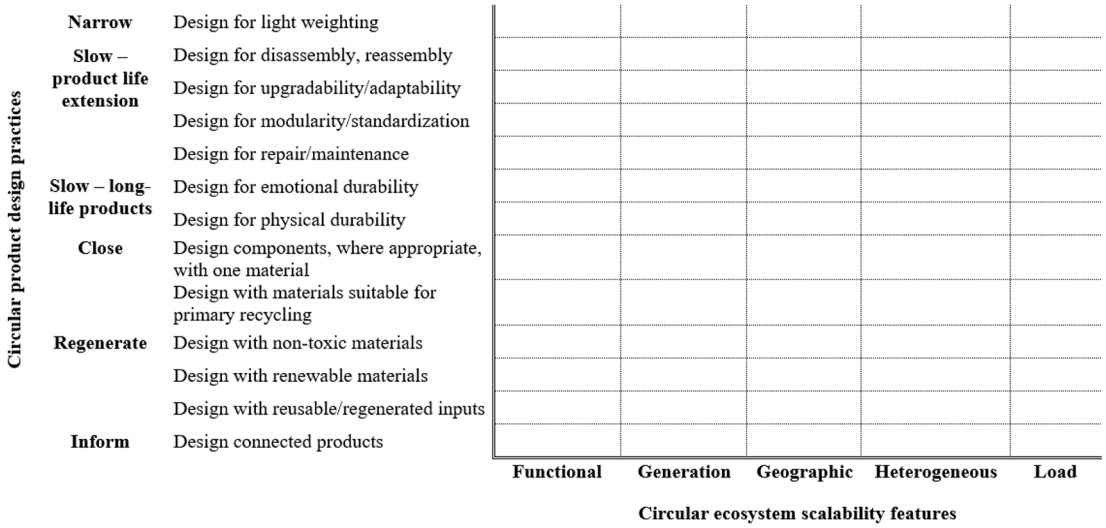

Fig. 1. Research framework.

Table 3
Circular ecosystem and focal company contextual information.

	Case study	A	B	C	D	E
Circular ecosystem contextual information	*Industrial sector*	Furniture	Flooring and wall surfaces	Furniture	Textile	Automotive
	Involves new actors that would not be involved with linear ecosystems	X	✔	X	✔	✔
Focal company contextual information	*Employees*	> 220,000	> 13,000	> 11,000	> 100,000	> 150,000
	Revenues [€ Billion]	> 40	> 3	> 2	> 22	> 54

Table 4
Brief description of the case studies.

Case study	*Brief description*
A	Case A is a company-centric circular ecosystem characterised by a focal company that offers furniture and household items and is committed to becoming fully circular and climate-positive by 2030. To meet this objective, the focal company designs its products according to CE principles. Moreover, the focal company believes that the transition from the linear economy to the CE should be pursued not alone but through collaboration. It is therefore disseminating CE principles among the actors already involved in its current linear ecosystem to turn it into a circular ecosystem.
B	Case B is a company-centric circular ecosystem characterised by a focal company specializing in the production of floor and wall surfaces. The focal company's objective is to minimize the impact of its products on the environment. Products are thus designed with reusable and regenerated inputs, which gives rise to two opportunities: first, circularity initiatives are promoted; and second, a larger network of suppliers can be involved as resources can be collected both from virgin and secondary material suppliers. Accordingly, the circular ecosystem, albeit not currently large, involves companies that would be not involved in a traditional linear ecosystem.
C	Case C is a company-centric circular ecosystem characterised by a focal company that manufactures furniture and architectural and technology products for offices, schools, and hospitals. The focal company is engaged in creating a collaborative ecosystem of players aiming at designing products according to CE principles and extending resources and products' useful lives. Not a large number of companies (e.g., suppliers) is involved in this collaborative ecosystem, at the same time the number keeps increasing thanks to the ease of disassembly of the final products. The circular ecosystem is therefore currently middle-sized, and it involves the same type of companies that would have been involved in a linear ecosystem, given that the main activity remains product design.
D	Case D is a company-centric circular ecosystem characterised by a focal company that is one of the main companies operating in the fashion industry on a global scale. Being a major player, the focal company is committed to drive change in its industry. The focal company aims to design all its products according to CE principles by 2025 and to achieve net zero by 2040. To meet these objectives, it is engaged in developing a circular ecosystem by (i) designing products according to CE principles, (ii) collaborating with suppliers and partners to support forward and backward material flows, and (iii) engaging customers in reuse, remanufacturing, and, lastly, recycling practices. The circular ecosystem is large and involves companies that would not have been involved in linear ecosystems.
E	Case E is a company-centric circular ecosystem characterised by a focal company that is a leading firm in the automotive industry and has built a dedicated CE factory for vehicles and mobility. The focal company's objective is to reduce its use of virgin materials by extending raw materials', components', and vehicles' useful lives for as long as possible. To meet this objective, designing vehicles according to CE principles is fundamental for the focal company. Moreover, to close resource loops, the focal company relies on a circular ecosystem composed of different actors engaged not only in remanufacturing, reuse, and recycle activities but also in research and innovation activities (start-ups and industrial and academic partners are involved in the circular ecosystem). The circular ecosystem is large and involves companies that would not be present in linear ecosystems.

empirical evidence and analytical discussion (Dubois & Gadde, 2002) and it is suitable to investigate novel research areas (Timmermans & Tavory, 2012), such as the interplay between circular product design and circular ecosystem scalability.

A content analysis (Weber, 1990) was performed to triangulate and cluster the information from diverse data sources. The qualitative coding procedure began with manual within-case coding, leveraging the circular product design practices (see Table 1) and the circular ecosystems scalability features (see Table 2) with the guidance of our research framework. Thereafter, we investigated and manually coded the link between each applied circular product design practice and the achieved scalability feature. As an example, Company B highlights that 'on our circular economy journey, we are always seeking to create healthier products that can be safely transformed into new ones, conserving natural resources and creating a positive impact on the environment. This often means collaborating with unlikely partners. This exemplary statement was coded to match (i) the regenerate circular product design dimension, in particular design with non-toxic materials and with renewable/regenerated inputs (as the company aims to design healthier products that do not harm the environment and that can be reused into a new cycle) and (ii) the heterogeneous scalability feature (as the company needs to collaborate with new, and uncommon, partners to accomplish its CE journey with healthier and reusable products). The objective of the analysis process was to integrate the research framework presented in Fig. 1 with exploratory empirical evidence. As a result, we mapped the applied circular product design practices and achieved scalability features for each case study into our integrative framework presented in Fig. 2.

4. Findings

4.1. Integrative framework overview

Fig. 2 illustrates the integrative framework which integrates the literature-based research framework with exploratory empirical evidence to answer our research question and to explain how to scale by design circular ecosystems. A total of 28 matches were identified, explaining the potential for circular design practices to enable circular ecosystem scalability. Different practices enable multiple scalability features, such as design for connected products that enables functional, generation, geographic, and load scalability. A given circular ecosystem scalability feature is enabled by multiple circular design practices, such as functional scalability that is enabled by the whole set of circular product design practices, except design for light weight.

Our integrative framework is among the first attempts to relate circular ecosystem scalability features with circular product design practices, offering a way for circular ecosystems to scale up by design and implement CE principles at a larger scale without hampering performance.

Below, we dive into each circular product design dimension and describe the scalability features enabled by each circular product design practice.

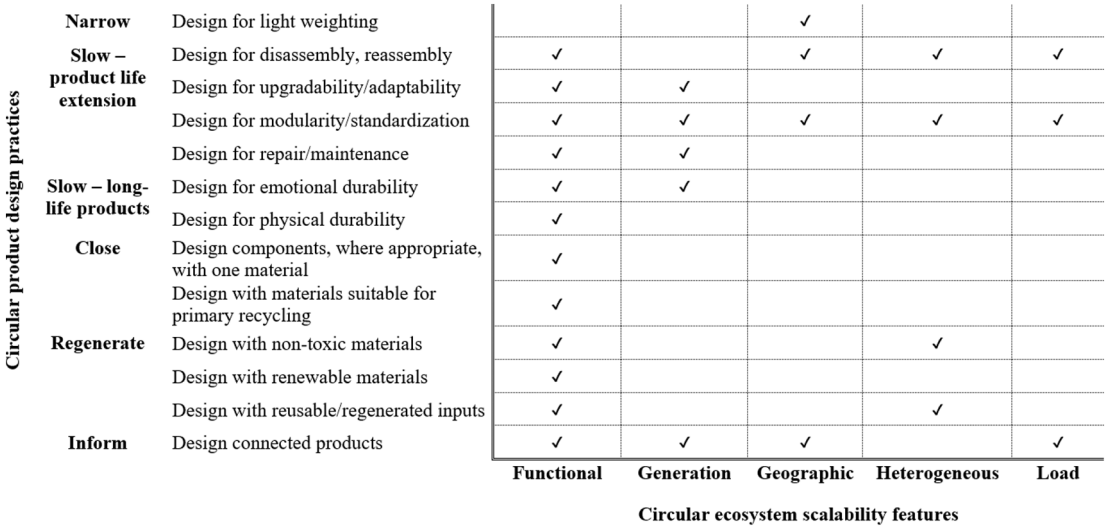

Fig. 2. Integrative framework: matches among circular product design practices and circular ecosystem scalability features.

4.1.1. Narrow

Design for light weight allows to reduce the extraction of primary resources, lowering the amount of material to be transported for production purposes. Lighter products are more easily handled and allow for more economically efficient transportation, particularly for dematerialized components and features that can be digitally managed. Design for light weight acts as an enabler for geographic scalability, making it easier and more economically viable to serve a large geographic market than that initially served by the circular ecosystem (in accordance with, e.g., Konietzko et al., 2020). This argument holds true for production, distribution, takeback and cycling of resources. For instance, Case A illustrates that the reduction in component weight is pivotal in establishing a more extensive geographic network, thereby enabling the central company operating within the circular ecosystem to expand its reach over time.

4.1.2. Slow – Product life extension

Design for disassembly and reassembly allows products to be easily disassembled and reassembled, rendering them more likely to adapt to different conditions by integrating other circular managerial practices and enabling ecosystems to respond to context changes and meet demand (as also pointed out by, e.g., Pialot et al., 2017). Hence, it can be argued that design for disassembly and reassembly enables functional scalability by enabling the implementation of additional circular practices when necessary. Furthermore, by designing products that adapt to different needs over time, including different suppliers and flow variations, design for disassembly and reassembly enables heterogeneous and load scalability. Different components can be supplied by different actors to those already within the ecosystem, and proper stock management of the different components can optimize activities when flow variations occur (see, e.g., Liu et al., 2021). Lastly, products with components that can be easily managed and transported by different actors enable to optimize transportation activities across larger areas, thus enabling geographic scalability. According to Case C, ease of disassembly is a critical factor in extending components' lifecycles and broadening material flows, enabling the focal company to expand its covered geographic area and cope with demand spikes.

Design for upgradability/adaptability allows for the continuous updating of products to new features, driven by the development of product innovation or new requests from final users, and new requirements, imposed by the most recent regulatory framework. For example, Case D considers that garments are designed with parts that could be easily upgraded, adapting them to the most recent fashion. In an industry characterized by significant resource consumption, such as the textile industry, the ability to seamlessly incorporate novel components into existing garments is paramount. The integration of a new component into a garment not only enhances its functionality but also prolongs its lifespan, thereby reducing the necessity for consumers to procure entirely new garments, which in turn decreases resource consumption. Meanwhile, design for adaptability can allow embracing agile experimentation and learning for improved circularity (Frishammar et al., 2025). Design for upgradability/adaptability thus enables generation scalability. Besides, additional circular managerial practices could be applied with upgradable products (e.g., offering an upgradeable product as product–service–system to final users) enabling thus functional scalability (in accordance with, e.g., Copani & Behnam, 2020).

Design for modularity/standardization allows for the design of easily upgradable products. If products have modular and standard components, it is easier for the ecosystem to easily replace and upgrade them by changing the standard key components impacting the products' performances. Hence, design for modularity/standardization enables generation scalability. As also pointed out by Case C, new features and regulatory requirements could easily be satisfied by changing or adapting the modular components of the focal company's products. Modular, standard product components also favor the compatibility of different material flows between multiple, different actors. It thus enables heterogeneous scalability given the ease of integration of different suppliers, as long as they meet the standardization criteria of the components, parts to be supplied. Design for modularity/standardization also enables actors to respond better to materials' load variations and to optimize stock to face supply and demand variations. As highlighted by Case E, vehicles' modularity is key to enable the ecosystem to cope more easily with demand spikes. The manufacturing of vehicles is characterized by complex and global ecosystems, the design of modular components across various vehicles models and typologies enables to optimize stocks and more easily cope with demand variations. Design for modularity/standardization enables the application of further circular managerial practices, such as the take-back-systems through the optimization of reverse logistics (in accordance with, e.g., Zikopoulos, 2022). Therefore, design for modularity/standardization enables functional scalability. Both reverse and forward flows can be optimized with modular products; thus, a larger geographic area can be served without negative impacts on the ecosystem's performance (as also pointed out by, e.g., Machado & Morioka, 2021) and geographic scalability is enabled.

Design for repair/maintenance allows for simplified repair and maintenance activities that can even be performed by final users following the proper instructions. Maintenance encompasses also product

upgrades. For instance, if a smartphone is designed for repair/maintenance, a major component can be substituted with an upgraded one during maintenance. The possibility to repair and maintain products raises the possibility of applying further circular managerial practices (in accordance with, e.g., Lüdeke-Freund et al., 2019). For instance, a product-service-system can leverage repairable products in order to ease the extension of its lifecycle. Therefore, design for repair/maintenance enables functional and generation scalability. According to Case E, vehicles are also designed to be easily repaired and maintained to keep up to date with newer regulatory standards or consumer needs, such as components enabling further connectivity (e.g., the utilization of Bluetooth connectivity facilitates the utilization of mobile phones in older cars, thereby ensuring compliance with legislation that prohibits the use of mobile phones while driving).

4.1.3. Slow – Long-life products

Design for emotional durability and *design for physical durability* aim to design products that last longer. These products are designed to adapt to changing contexts and user needs, with various circular managerial practices being applied. If the user is attached to the product or the product is still in good conditions, the user can update the product to fit the newest trends (in accordance with, e.g., Lüdeke-Freund et al., 2019). For example in Case A, the product needs to be designed to be long-lasting, not only physically but also emotionally, and it designs products with users' needs in mind so that users then become emotionally attached to the products and can personalize them according to the latest trends. Therefore, design for emotional durability and design for physical durability enable functional and generational scalability.

4.1.4. Close and regenerate

The circular design practices belonging to the close and regenerate dimensions enable functional scalability, similarly to practices belonging to the slow – long-life products dimension. Indeed, the circular design practices related to close and regenerate dimensions, facilitate the implementation of further circular managerial practices and renovation activities according to CE principles. Considering the close dimension, *designing products with only one material, if feasible* can facilitate the implementation of a take-back-system and other renovation or recycling activities. In addition, Case B considers that when the lifecycle of products can no longer be extended, closing the loop through recycling is facilitated thanks to *design for primary recycling*. Considering the regenerate dimension, *designing products with non-toxic materials* makes it easier to adapt to the ever-changing competitive environment without having to comply with specific safety standards and regulations. In Case D, further circularity initiatives are enhanced when products are designed with non-toxic and renewable materials. Case A also shows that products made with single, non-toxic, renewable, and reusable materials promote further circularity. Additionally, design with non-toxic materials could positively impact the circular ecosystem's ability to manage material flows from different suppliers. As non-toxic materials are not required to comply with specific safety standards and regulations, more suppliers could join the potential circular ecosystem (as also pointed out by, e.g., Schoden et al., 2022). Therefore, design with non-toxic materials enables heterogeneous scalability. Besides, design with reusable, regenerated materials enables also heterogeneous scalability. Indeed, in Case B, a larger network of suppliers can be involved, as resources can be collected not only from virgin but also from secondary material suppliers.

4.1.5. Inform

Design for connected products facilitates the tracking of products in forward and reverse logistics activities over a large geographical area and with increased flows, thanks to the data provided by the product itself embedded with digital technologies, such as RFID sensors. As shown by Case D, designing connected products increases the geographical reach of the circular ecosystem by enabling remote monitoring, making it easier to respond to any variations in flows, even in real time, thanks to the data collected and analyzed by digital technologies. Besides, according to Case E, further circularity initiatives are promoted by designing products embedding sensors that signal if and when maintenance or remanufacturing is needed by promoting, for instance, predictive and preventive maintenance that can extend the lifecycle of products. Therefore, design for connected products enables functional, geographic, and load scalability. In Case C, digital technologies can provide innovative services through which a building's occupants use patterns, well-being can be not merely monitored but also optimized. Indeed, thanks to the design of connected products, personalized furniture updates could be offered to users to optimize the environment in which people work, study and live. Moreover, connected products can be updated 'over the air' through updates to the embedded digital technologies, such as software components in vehicles as highlighted by Company D. Hence, design for connected products enables generation scalability (in accordance with, e.g., Ertz et al., 2022).

4.2. The ranking of circular product design practices

The identified circular product design practices contribute differently to circular ecosystem scalability. For instance, it is evident from Fig. 2 that circular product design practices belonging to the close dimension enable solely one scalability feature, namely, functional scalability. Conversely, designing connected products, belonging to the inform dimension, enables four different scalability features: functional, generation, geographic, and load. To give a clearer overview, Fig. 3 shows the 'multi-enabling' role of each circular design dimension, that is, the number of circular ecosystem scalability features it enables.

From Fig. 3, we can distinguish three clusters of circular design dimensions. First, the selective cluster involves circular design dimensions enabling a few scalability features, i.e., one or two. Most of the circular design dimensions belong to this cluster. Second, the multi-purpose cluster groups circular design dimensions enabling many (i.e., between three and four) scalability features. Only one circular design dimension belongs to this cluster. Third, the all-in cluster groups circular design dimensions enabling the whole set of scalability features. Only one circular design dimension belongs to this cluster.

The whole set of scalability features can be achieved by applying circular product design practices belonging to the slow – product life extension dimension; thus, this dimension has particular relevance to the systematic implementation of the CE. The circular product design practice belonging to the inform dimension has the second highest relevance as it enables four different scalability features. Lastly, the narrow, slow – long-life products, close, and regenerate dimensions are lower ranked as they only enable a few scalability features.

5. Discussion

To understand the role of circular product design in enabling the scalability of circular ecosystems, this research merged two perspectives: circular product design practices and circular ecosystem scalability features. Considering the first perspective and *research on circular product design*, the findings indicate that such circular product design practices allow moving from the application of CE at the company level to that at the ecosystem level, positing as a key to achieve and spread systemic CE. By building on previous circular product design literature (see, e.g., Bocken et al., 2016; Lüdeke-Freund et al., 2019) and proposing a novel integrative framework interlinking circular product design practices and scalability features, this study contributes to investigating the implementation of CE principles especially in environmentally burdensome sectors (see, e.g., Aguiar & Jugend, 2022). Analysis of the number of circular ecosystem scalability features enabled by each circular product design practice, also reveals that design for modularity/standardization is the most relevant to scale up circular ecosystems by being interlinked with the whole set of circular ecosystem scalability

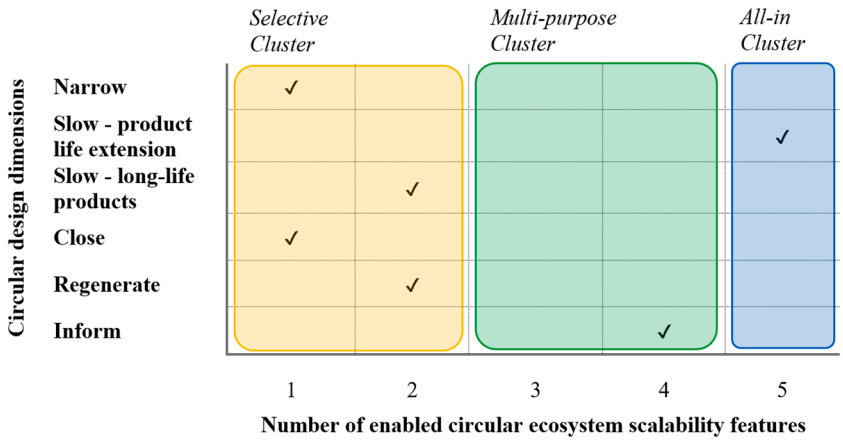

Fig. 3. The ranking of circular design dimensions for circular ecosystem scalability.

features.

Considering the second perspective and *research on circular ecosystem scalability*, we are among the first to extend company-level circular design practices to deepen their role in enabling circular ecosystem scalability. The transition towards the CE requires a systemic change in the whole set of actors involved in circular resources and material flows to collaborate (Fernández-Arribas et al., 2024). Our framework supports previous research that has pointed to the need to achieve a systemic CE (see, e.g., Marini et al., 2024) and focuses on circular ecosystems by clearly interlinking the enabling role of circular product design practices with circular ecosystem scalability features. This finding confirms and expands findings from previous research in the CE field regarding circular ecosystems (see, e.g., Aarikka-Stenroos et al., 2021; Kaipainen et al., 2023). As circular ecosystem scalability is a promising research area in facilitating businesses' successful transition towards the CE (Han et al., 2023; Sandberg, 2023) and contribute to achieve decarbonization, it is surprising how little research has been conducted in this field (see, e.g., den Hollander et al., 2017; Densley Tingley et al., 2017). Our integrative framework deals with this under-explored research area and it posits that the scalability of circular ecosystems is critical to (i) implementing CE not only at company level but also at ecosystem level as a systemic phenomenon, (ii) guaranteeing a synergic and systemic flow of resources, materials, and products avoiding mismatches, (iii) keeping up with the increasing demand for sustainable products, (iv) adjusting internal resources to cope with evolving demand and/or supply variations in the ecosystem, and (v) diffusing CE principles into large geographic areas.

From our integrative framework presented in Fig. 2, functional scalability emerges as the most widespread scalability feature. This finding is aligned with the CE objective of value preservation through practices aimed at extending products' lifecycle and closing resource loops and achieve decarbonization (see, e.g., Bocken et al., 2016). This CE objective aligns with the functional scalability feature's objective, namely, to apply further circular managerial practices whenever needed to close resource loops. The alignment between the CE objective and functional scalability objective also explains why the functional scalability feature is the most sought-after and widespread. To achieve this objective, products must first and foremost be durable and long-lasting. Ease of disassembly and reassembly is another crucial enabler for the implementation of different technological cycles (e.g., recycling). This confirms Bocken et al.'s (2016) proposal that long life, life extension, and dis- and reassembly are among the main circular product design strategies for the CE not only at company level but also at ecosystem level.

Our insights into circular ecosystem scalability allow a focus on those scalability features that appear most effective to overcome the recognized barriers to the innovation of circular businesses (Taddei et al., 2022; Zucchella & Previtali, 2019). Therefore, we promote the relevance of circular ecosystem scalability through circular product design practices and encourage scholars to further investigate this topic (as also emphasized by, e.g., Aarikka-Stenroos et al., 2022; Machado & Morioka, 2021).

6. Conclusions

This paper is one of the first attempts to investigate circular ecosystem scalability. We do so by discussing the role of circular design practices implemented by companies within circular ecosystems as enablers of scalability features. We developed an integrative framework with 28 matches between circular design practices and circular ecosystem scalability features.

The paper presents three main limitations. First, as the framework is cross-sectional by nature, a longitudinal approach could be followed to identify the most effective timing for different circular product design practices in scaling up circular ecosystems. Second, our purpose was not to focus on a single circular ecosystem scalability feature, but on the whole set of scalability features and investigate the role of the different practices in enabling it. Third, we did not define the interplay among various features of scalability to gain the first-hand understanding to the roles of specific circular design practices in the scale-up of a given circular ecosystem. These limitations could be explored by future research as promising future research avenues.

For scholars in the CE field, this paper bridges the gap in the extant academic literature by providing a novel framework clarifying how circular ecosystem scalability is enabled by different circular product design practices. In particular, the contribution of this paper to extant literature is threefold. First, we identify which circular design practices have the highest potential for enabling circular ecosystem scalability, namely design for modularity/standardization. Second, we advance circular ecosystem research by understanding which features allow circular ecosystem scalability, namely functional scalability feature. Third, we deepen the understanding of circular ecosystems as multi-level, systemic phenomena.

Additionally, we provide advice to managers and policymakers. The findings encourage managers, particularly those in environmentally burdensome sectors, to be aware of and implement circular product design practices that allow the scale-up of circular ecosystems, thus spreading the CE as a systemic phenomenon to achieve decarbonization. In practice, the integrative framework suggests that managers should focus on circular product design practices to achieve circular ecosystem scalability. Managers could focus on design for modularity/standardization because this is interlinked with the whole set of circular ecosystem scalability features and therefore has the most promising role in enabling such scalability. For policymakers willing to efficiently

tackle climate change and environmental threats and to achieve decarbonization and net-zero targets, this paper suggests creating favorable conditions for circular ecosystem scalability. For instance, policymakers could develop supporting measures for the application of certain circular product design practices based on whichever circular ecosystem scalability feature is deemed most important to achieve in that particular context and geographical area.

To conclude, this paper represents one of the first contributions to investigate the scalability of circular ecosystems through circular design practices, and develops a first-of-its-kind integrative framework. Design for modularity/standardization holds the most promise in enabling the scalability of circular ecosystems, and could thus represent the key practice to 'scale by design' circular ecosystems for driving the necessary systemic change towards the CE.

CRediT authorship contribution statement

Lucrezia Sgambaro: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Jenni Kaipainen:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Davide Chiaroni:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

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

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Data availability

The authors do not have permission to share data.

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