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Commercializing circular economy innovations: A taxonomy of academic spin-offs

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A R T I C L E I N F O

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A B S T R A C T

Innovation and the commercialization of new technologies are seen as important drivers of the transition to a more sustainable development. An actionable strategy to achieve such a transition is outlined in the European Union strategy on resource efficiency and the development of a circular economy (CE). Academic spin-offs (ASOs) are new ventures based on scientific research that play an important role in commercializing technological innovations. However, the potential role of ASOs in the CE transition has not been systematically examined. We build on a unique dataset covering the population of ASOs in Norway and coded newspaper articles to identify potential CE-related innovations being commercialized by these firms. Using multiple correspondence analysis and clustering analysis, the ASOs were empirically classified along two dimensions related to the types of innovation (i.e., product or process) and the types of CE principle (i.e., narrow, slow, or close the production-consumption loop). Five clusters of CE-related ASOs were identified (i.e., smart product-service providers, technical process enhancers, biochemical cycle extenders, renewables providers, and biosphere regenerators), each having specific roles in the CE transition. This taxonomy can serve as a basis for more systematic comparisons of CE-related innovations across different firms and contexts. We conclude by outlining an agenda for further research and implications for how policies can harness the potential of ASOs to foster CE innovations.

1. Introduction

Science, technology, and innovation play a key role in addressing societal challenges, such as the excessive extraction and use of natural resources and associated challenges with pollution and waste (Schot and Steinmueller, 2018). With its main aim of addressing natural, environmental, and societal issues, the circular economy (CE) has emerged as a significant concept for transforming economies from the linear ‘take-make-dispose’ system to the circular ‘make-use-return’ system (Geissdoerfer et al., 2017). In the European Union's (EU's) Circular Economy Action Plan 2020, the European Commission has set ambitious goals for transitioning to a stronger CE, in which obsolete materials and goods are regenerated and restored to narrow, slow, and close the production-consumption loop.

Technological innovation is essential in such a transition towards a CE because numerous initiatives rest on the implementation of new technology to create a circular system (Cainelli et al., 2020). Hence, the rapid commercialization of scientific knowledge and technology to improve the circularity of physical resource flows will likely be a key enabler for the CE transition to succeed. Radical and sustainability-related innovations are more likely to be commercialized by entrepreneurial ventures, such as spin-offs and start-ups, than by large firms already established in the market (Hockerts and Wüstenhagen, 2010; Schaltegger et al., 2016; Kennedy et al., 2017; Homfeldt et al., 2019). With fewer asset liabilities, flexible organisational structures, and open technological mindsets, entrepreneurial firms often take the pioneering role as opportunity explorers and pursue sustainability goals (Homfeldt et al., 2019). Conversely, large firms with organisational inertia and locked-in paths, but better R&D financing, tend to take follower positions to exploit market opportunities that occur when technological trajectories are changing, when new policies are enacted, or when consumers become increasingly concerned about environmental and social issues (Schaltegger et al., 2016; Hockerts and Wüstenhagen, 2010). Large firms are inclined to adopt marginal CE strategies, such as recycling, but rarely shift their whole organisational paradigms (Bocken et al., 2017; Henry et al., 2020). By contrast, innovative spin-offs and start-ups can introduce disruptive innovations, design holistic circular business models, and thereby create substantial CE impacts (Henry

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et al., 2020).

The existing CE literature predominantly focuses on large established firms, while the important role of innovative start-ups remains only marginally studied (Henry et al., 2020). This is unfortunate because the CE frameworks and strategies used by large established firms may not be applicable for small spin-offs and start-ups (Henry et al., 2020; De Jong and Marsili, 2006). By commercializing scientific research developed at academic institutions, academic spin-offs (ASOs) are highly innovative start-ups with the potential of creating high economic (Vincett, 2010) and societal impacts (Fini et al., 2018). ASOs are potential forerunners by facilitating knowledge spillovers from the research base (Audretsch and Keilbach, 2008) and developing innovations (Shane, 2004). In the CE transition, ASOs may be essential innovators by commercializing new technologies and contributing to radical product and process CE innovations in other firms (Pavitt, 1984; Autio, 1997). However, the potential role that different types of ASOs can play in commercializing CE innovations is not well understood. Furthermore, there are no clear definition and systematic measurement of CE innovations considering both CE attributes and innovation attributes. At this current stage, CE studies mostly borrow the concepts of eco-innovation or sustainable innovation to indicate CE innovation, but eco-innovation and sustainable innovation may not be able to fully reflect all CE characteristics and CE principles.

This paper addresses these gaps by examining the potential role of ASOs in introducing innovations that improve the circularity of the economy. This study explores the following question: *What types of CE innovations are commercialized by ASOs?* To answer this question, we analysed a comprehensive dataset covering the population of 373 ASOs established between 1999 and 2011 on the basis of academic research at universities and research institutes in Norway. By searching media archives, we identified 60 ASOs commercializing CE innovations. We used Multiple Correspondence Analysis (MCA) and Clustering Analysis to define types of CE innovations and identify five clusters of CE-related ASOs according to the types of innovations they commercialized. This taxonomy provides empirical evidence about the different types of CE innovations commercialized by ASOs, which enhances the understanding of the roles of ASOs in the CE transition. Our taxonomy forms the basis for discussing implications for policy and future research.

2. Literature review

2.1. CE and the role of innovation

CE is defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops” (Geissdoerfer et al., 2017, p. 759). At the firm level, firms can adopt CE strategies in their businesses to enable circularity in their systems. CE strategies act as “how-to” guidelines and are often operationalized as the ‘R’ strategies (Kirchherr et al., 2017). The most widely used is the ‘3R framework’ which refers to the reduce, reuse, and recycle strategies (Morseletto, 2020; Lieder and Rashid, 2016; Kirchherr et al., 2017). The EU introduced the ‘4R framework’ for the official EU's Circular Economy Action Plan, including reduce, reuse, recycle, and recover. Additionally, the CE strategy of extending product longevity is also often included and involves designing for durability, quality, and reliability to maintain longer product utilities (Bocken et al., 2016). Some scholars proposed an extended ‘6R framework’ or even ‘9R framework’ entailing further CE strategies such as repair, remanufacture, refurnish, and rethink (Morseletto, 2020; Kirchherr et al., 2017). The selection of CE strategies in firms or research depends on business strategies and research cases. In this study, we focus on the five strategies reduce, reuse, recover, recycle, and extend product longevity.

These five strategies correspond to the general principles of narrowing, slowing, and closing the production-consumption loop (Bocken et al., 2016; Konietzko et al., 2020). *Narrowing the loop* involves the reduce strategy and resource efficiency to decrease resource consumption, make production cleaner and generate less waste. To some extent, the *narrowing the loop* CE principle relates to the resource efficiency of the linear economy because they both aim for higher efficiency and cost-saving by introducing new technologies into production processes (Bocken and Ritala, 2022). However, *narrowing the loop* is a crucial principle of the CE and this point of view is reflected in several national and regional plans. The EU's Circular Economy Action Plan 2020 highlights the ultimate goals of CE to keep “its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade” (European Commission, 2020, p.2).

The *slowing the loop* CE principle focuses on increasing product lifetime and maintaining products in use. This strategy can be achieved by enhancing product quality, maintaining and repairing products (Bocken and Ritala, 2022) through the reuse of products and extending product longevity. This principle is necessary to solve the issues that “many products break down too quickly, cannot be easily reused, repaired or recycled, and many are made for single use only” (European Commission, 2022, p.3). Finally, the *closing the loop* CE principle focuses on reusing and recycling materials and products post-usage through downcycling activities (i.e., burning and converting organic wastes into fuels) or upcycling activities (i.e., recycling materials to produce new forms of products) (Bocken and Ritala, 2022).

The CE is characterised by two main cycles: the technical cycle and the biological cycle of products and materials (Murray et al., 2017; Jabbour et al., 2019; Bocken et al., 2016). CE improves the technical cycle by increasing the technical life of the products to maintain products and technical components longer in the production-consumption loop, maximising product utility by ownership sharing, minimising value loss of products, and enhancing the technical production and consumption processes by advanced technologies such as digital technologies (Huynh and Rasmussen, 2021). Regarding the biological life of products and materials, CE aims to retain values of biomass through the activities of recycling or by-product exchanges, shift to renewable biomass, biofuels, and biomaterials, as well as to increase the lifespan of bioproducts in the loop to reduce wastes.

Innovation plays a crucial role in the CE transition (Smol et al., 2017; Konietzko et al., 2020) by creating necessary changes in products, services, and production systems, which enable more circular resource flows (Cainelli et al., 2020). Shifting towards a new CE paradigm of the technical and biological cycles requires innovation on multiple levels of the economy (de Jesus et al., 2018). At the macro level, CE innovation concerns the implementation of policies and regulations on an international, national, or regional scale. CE innovation at the *meso* level involves inter-actor collaboration, such as industrial symbiosis (de Jesus et al., 2018). Industrial symbiosis is a system to enhance integration and collaboration among actors in the same industrial system or different sectors to exchange by-products (i.e. residuals of one industry as resource inputs of another industry), optimize resource efficiency, increase material utility, and reduce greenhouse gas emissions (Domenech et al., 2019; Sun et al., 2017; Provin and de Aguiar Dutra, 2021). Micro-level CE innovation depends on the activities of individual firms (de Jesus et al., 2018) that implement circular business model innovations and technological innovations based on relevant CE strategies (Ghisellini et al., 2016).

Diverse types of innovation are required to transform the linear economy into a CE (de Jesus et al., 2018). Most CE-related innovation studies have focused on four main aspects: circular business model innovations, technology and digital technology, external and internal influences, and multiple levels and multiple actors. Research on circular business model innovation, one of the dominant literature streams, explored how firms may apply CE strategies and shift production processes from linear to new circular business models. Circular business model innovation is referred to as “a shift from a linear to a circular business model” (Linder and Williander, 2017, p. 194) or as “the conceptualisation and implementation of circular business models, which comprises the creation of circular start-ups, the diversification into circular business models, the acquisition of circular business models, or the transformation of a business model into a circular one" (Geissdoerfer et al., 2020, p. 8).

Circular business model innovation research has moved from a traditional view of the business canvas framework to more heterogenous, interdisciplinary perspectives of business model innovation and CE (Pieroni et al., 2019). Henry et al. (2020) examined circular start-ups and identified six types of circular business models in response to CE strategies, relating to design-based (i.e., reduce or reuse), waste-based (i.e., recycle or recover), platform-based (i.e., various CE strategies), service-based (i.e., various CE strategies), nature-based (i.e., regenerate), and other types (i.e., reduce, reuse, or recycle). Linder and Williander (2017) revealed that some circular business models relating to the reuse and remanufacturing strategies may induce some challenges (e.g., innovation uncertainty) for the entrepreneurs.

Several studies relating to innovation for the CE focus on specific technologies, for example, the emergence of digital technologies and automation in the CE transition (Chauhan et al., 2022; Despeisse et al., 2017; Suchek et al., 2021). Ranta et al. (2021) investigated how digital technologies (i.e., data collection, data integration, data analysis) may enable radical and incremental circular business model innovations. Another stream of research explored the drivers and barriers of CE innovation. Cainelli et al. (2020) found that environmental policy and demand-side factors were significant drivers for CE-related innovations. De Jesus and Mendonça (2018) emphasized that hard factors (e.g., technical, economic, financial, or market) and soft factors (e.g., institutional, regulatory, social, or cultural) contribute to the pathways of CE-related innovations to the CE 'transformation turn'.

The significant role of innovation for the CE is widely recognised but the research about CE-related innovations is still relatively generic and fragmented, leaving the relationships and mutual effects between CE and innovation yet to be fully explored (de Jesus et al., 2018). A more holistic view that integrates both innovation and CE attributes is lacking. De Jesus and Mendonça (2018) highlighted the significant need for better integrated, systematic views of innovation and CE research to provide a clearer understanding of how the CE transition can be facilitated. Hence, we consider CE innovation by combining both CE and innovation perspectives (Murray et al., 2017).

2.2. Towards a definition of CE innovation

A consolidated definition of CE innovation is lacking (Cainelli et al., 2020). To examine innovation for the CE, scholars tend to borrow the 'eco-innovation' concept (De Jesus and Mendonça, 2018). Eco-innovation is defined as innovation that contributes to improving environmental and ecological issues and to progressing sustainable development (OECD, 2009; Carrillo-Hermosilla et al., 2010; Rennings, 2000). Eco-innovation and CE innovation are related in several ways, such as their similar goals of decreasing environmental impacts, reducing pollution, and using natural resources and energy responsibly (Carrillo-Hermosilla et al., 2010; de Jesus et al., 2018). However, eco-innovation refers to sustainability as a generic, holistic concept aiming to benefit the environment, economy, and society at large without prescribing how to achieve it (Elkington, 1998; Geissdoerfer et al., 2017). CE innovation provides more explicit, pragmatic, and applicable guidance of specific strategies (e.g., reduce, reuse, recycle, or recover) for implementation at the firm level (Geissdoerfer et al., 2017). Hence, not all eco-innovation may reflect CE principles and the research field needs a more specific definition of CE innovation (de Jesus et al., 2018).

Because CE includes a variety of distinct strategies, different types of innovations are likely to vary in their potential to generate CE impacts. Hence, to develop a more systematic understanding of CE innovation types, innovation variables should be taken into account. We build on the defining attributes of innovation and the key CE principles to propose the following definition of CE innovation: *incremental or radical improvements of products, services, production processes, or business models that minimise the use of resource inputs and the generation of waste through the principles of narrowing, slowing, and closing the production-consumption loop*.

2.3. Towards indicators to measure CE innovations

Several indicators are used to measure the characteristics of innovations, such as product versus process, knowledge domains, and patent (see Table 1). Contexts such as market competitiveness, environmental issues, and social issues can determine firm-level innovation characteristics to a great extent (Autio et al., 2014; Dziallas and Blind, 2019; Souitaris, 2002). Hence, contextual variables are important for measuring and constructing the taxonomies of innovation (Dziallas and Blind, 2019). CE strategies may also be the significant contextual determinants for innovation given their potential influences on innovation strategies at micro, *meso*, and macro levels. This linkage between CE and innovation is closely intertwined because innovation is essential to CE (de Jesus et al., 2018). At the same time, CE strategies can also impact the management of innovation, particularly at the firm level (Blomsma et al., 2019).

Measures and taxonomies of CE-related innovations tend to be centred on CE attributes, such as circular business models and CE strategies (Smol et al., 2017; Blomsma et al., 2019; Henry et al., 2020; de Jesus et al., 2018) but less on innovation attributes. For example, to build a typology of circular start-ups, Henry et al. (2020) used determinants such as CE strategies (i.e., regenerate, reduce, reuse, recycle, or recover), downstream (i.e., product-service system or consumers' involvement) versus upstream activities (i.e., industrial symbiosis or circularity standards), and core and enabling technologies. However, conventional innovation variables such as technology domain, product versus process orientation, knowledge domain, research organisation, and collaboration have typically not been included in the investigations of CE-related innovations.

In our classification, CE innovations demonstrate inherent attributes of innovation, for example, process-oriented, product-oriented, or business model innovation; radical or incremental innovation; innovation based on basic or applied research; innovation based on patented or non-patented technology; and based on different technologies. Thus, we propose a novel approach to examining CE innovations by considering both conventional innovation attributes and CE attributes (see Table 1).

Identifying CE innovation attributes is crucial to constructing a taxonomy of CE-related firms. Classifications of innovative firms rest on the assumptions that the nature of the technology at hand shapes firm behaviour and that innovative firms have distinguishable innovation

Table 1
Elements and indicators of innovation constructs.

Determinants	Indicators	Example studies
Nature of innovation	Product and process	Pavitt (1984), De Jong and Marsili (2006), Evangelista (2000), Tether and Tajar (2008), Peneder (2010)
	Sectors and technology domains	Pavitt (1984), Evangelista (2000), Autio et al. (2014), Souitaris (2002)
Knowledge & research	Basic and applied research	Carayol (2003), Grinstein and Goldman (2006)
Means of innovation	Patents	Carayol (2003), Peneder (2010)
Network	Collaboration with industry partners	Evangelista (2000), Souitaris (2002), De Jong and Marsili (2006)
	Collaboration with academic partners	Carayol (2003), Tether and Tajar (2008), Souitaris (2002), Evangelista (2000), Dziallas and Blind (2019)
Contextual factors	Societal, environmental, and CE influences	Smol et al. (2017), Autio et al. (2014), Luz et al. (2015)

patterns (De Jong and Marsili, 2006; Audretsch et al., 2020). Pavitt (1984)'s seminal taxonomy of innovation modes illustrates how firms can be differentiated with regard to sectoral technologies, institutional sources and nature of technology, and characteristics of innovating firms. The author's taxonomy distinguished four types of firms (i.e., supplier-dominated firms, large-scale producers, specialised suppliers, and science-based firms). In particular, science-based firms can play an important role in the CE transition because of their role in providing knowledge and technology to other firms (Autio, 1997; Pavitt, 1984).

ASOs are set up to commercialize scientific research and are characterised as highly innovative firms (Colombo and Piva, 2012) with the potential of transforming industries (Colombo and Piva, 2012) and local economies (Pisano, 2010; Aaboen et al., 2016). However, ASOs are relatively heterogeneous in their potential of generating impacts depending on their technological and institutional backgrounds (Garnsey and Heffernan, 2005). Therefore, the characteristics of ASOs may have important implications for their impacts on the economy and society, but empirical studies on these relationships are missing (Fini et al., 2018). Hence, a taxonomy of CE-related ASOs is important for understanding whether and how different firm types are commercializing different types of CE innovations.

To explore our research question related to the types of CE innovations commercialized by ASOs, we develop two sub-questions: (1) *what are the characteristics of CE innovations commercialized by ASOs?*; and (2) *what are the clusters of CE-related ASOs?* The study is focused on the context of ASOs and classifies ASOs according to their various CE innovations. Fig. 1 illustrates the conceptual framework for this study including the selected innovation and CE variables used (see more details in Section 3.2).

3. Method

3.1. Data

We obtained our sample from a database compiled by the Research Council of Norway comprising the population of 373 Norwegian ASOs established between 1999 and 2011. The ASOs were new ventures established to commercialize research results from publicly funded research organisations and were reported annually to the database. About two-thirds of the ASOs originated from universities and one-third from research institutes (Mathisen and Rasmussen, 2022). Similarly to other developed countries, the creation of ASOs has been stimulated by the Norwegian government and research organisations in an effort to increase research-based value creation (Fini et al., 2017).

Our data collection and coding process entails three main stages as shown in Fig. 2. In the first stage, we relied on collected data for the whole population of 373 ASOs. This data included the firms' annual reports that are mandatory for all firms in Norway (including the statement by the board of directors, detailed financial statements approved by a registered public accountant, and notes), all corporate announcements registered on the firms, obtained from the National Register of Business Enterprises in Norway, and patent data collected from the Norwegian Industrial Property Office. This extensive longitudinal data from 1999 until 2019 allowed us to map the firms' financial activities (e.g., sales, revenues, and assets) and operational events (e.g., survival, patent, and technology transfer) from their establishment until 2019 or exit. By using a comprehensive newspaper archive (i.e., A-tekst/Retriever) and internet search engines, we identified and downloaded 4252 articles written about 295 of the ASOs in the population of 373 firms. We excluded the remaining 79 ASOs that were early failures with no media coverage.

In the second stage, we selected our sample of ASOs with CE potential impacts. To identify CE-related ASOs and be able to code CE innovation variables, we primarily used media-coverage data. However, we also consulted other sources, such as company websites, annual reports, and financial statements to complement the news articles and achieve a more detailed understanding of the ASOs' CE innovations. We coded ASOs with CE potential as '1' and '0' otherwise. Notes were written down to justify the decisions. For example, one ASO developed a new chemical gel to reduce water consumption by 35 % and increase oil recovery by 30 % during oil drilling. This ASO's innovation was coded as the reduce strategy. Another ASO developed a technology to convert lignocellulosic biomass and organic residues to transportation fuels. The CE innovation of this ASO was coded as the recover strategy. After this round, a sample of 60 ASOs that commercialized CE-related innovations was obtained. The CE-related ASOs introduced different advanced technologies (e.g., digital technology, nanotechnology, biotech, energy and environmental technology, and material technology) and were involved in various sectors (e.g., oil and gas, processing, aquaculture, marine, energy, and environment). The medical technology and pharmacy sectors had no CE-related ASOs. A majority of CE-related ASOs in the sample (about 43 %) introduced digital technologies (e.g., sensors, digital platforms, software, application, and 3D models) and about two-thirds of the firms introduced process innovations. The reduce strategy and the optimize model were the most used ones by the ASOs.

In the third stage, we coded the remaining CE and innovation variables. This stage entails qualitative coding followed by quantitative coding. In the qualitative coding, we re-read the data for the 60 CE-

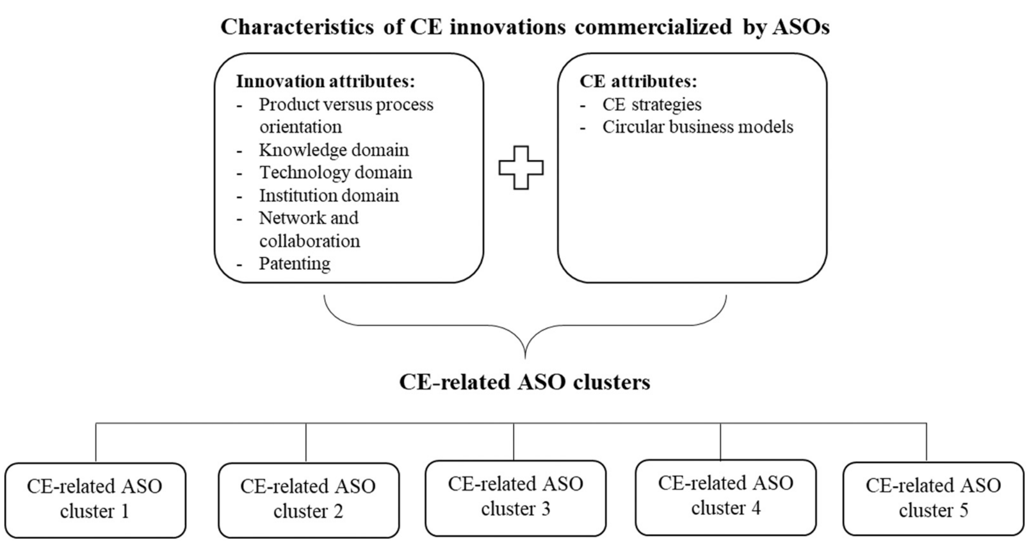

Fig. 1. The conceptual framework.

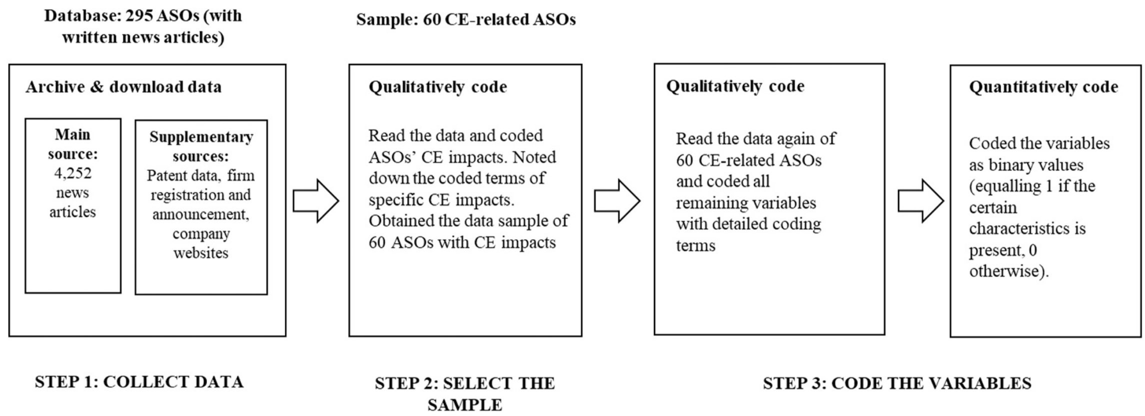

Fig. 2. The process of data collection and coding.

related ASOs, identified relevant article contents, and assigned them to variable categories that reflected key innovation attributes and CE attributes. Then, we quantified these qualitatively coded terms and coded twenty-one variables as binary values equalling '1' if the ASO exhibited the given attribute and '0' otherwise.

To improve coding reliability and reduce perception bias, the first author of this article and a research assistant independently coded the data. Before coding, the coders were trained to fully understand the

Table 2
Innovation and CE-related variables used in this study.

	Category	Variable	Label	Description
Innovation characteristics	Technology domain	Digital technology	Dig	=1 if the CE innovation is involved in digital technology =0 otherwise
		Material technology/ nanotechnology	Mat. nano	=1 if the CE innovation is involved in material technology/ nanotechnology = 0 otherwise
		Biotechnology/chemical	Bio.che	=1 if the CE innovation is involved in Biotechnology/chemical technology = 0 otherwise
		Energy/environmental technology	Eng	=1 if the CE innovation is involved energy or environmental technology = 0 otherwise
		Maritime technology	Mar	=1 if the CE innovation is involved maritime technology = 0 otherwise
	Product versus process	Product innovation	Prod	=1 if CE innovation of the firm is product oriented =0, otherwise
		Process innovation	Proc	=1 if CE innovation of the firm is process oriented =0, otherwise
	Basic versus applied research	Basic research	SB-gen	=1 if the CE innovation of the firm is based on basic research =0, otherwise
		Applied research	SB-sac	=1 if the CE innovation of the firm is based on applied research =0, otherwise
	Academic institution	Research institute	RI	=1 if the firm is originated from the research institute =0, otherwise
		University	Uni	=1 if the firm is originated from the university =0, otherwise
	Industry partnership	Industry partnership	Ind	=1 if the CE innovation involves in a industry partnership =0, otherwise
	Patent	Patent	Pat	=1 if the CE innovation is patented = 0, otherwise
Circular economy characteristics	CE strategy	Reduce	Red	=1 if the CE innovation involves the reduce strategy =0, otherwise
		Recover	Rec	=1 if the CE innovation involves the recover strategy =0, otherwise
		Extend product longevity	Ext	=1 if the CE innovation involves the extend product longevity strategy =0, otherwise
		Recycle/reuse	Rec.Reu	=1 if the CE innovation involves the recycle or reuse strategy = 0, otherwise
	Circular business model	Regenerate	Reg	=1 if the CE innovation is related to the 'regenerate' business model =0, otherwise
		Optimize	Opt	=1 if the CE innovation is related to the 'optimize' model =0, otherwise
		Virtual	Vir	=1 if the CE innovation is related to the 'virtual' model =0, otherwise
		Loop	Loop	=1 if the CE innovation is related to the 'loop' model =0, otherwise

coding framework and terminologies. In the case of coding disagreement, the two coders compared and discussed their coding, and a third coder was consulted to serve as the judge.

3.2. Innovation and CE-related variables

The quality and reliability of classifications are dependent on the selection of variables, which should be based on both theoretical and empirical considerations (De Jong and Marsili, 2006). We were able to include key innovation and CE variables as shown in Table 2 and outlined below.

3.2.1. Innovation variables

Technology domain refers to the type of technology the innovation is related to, which is found to impact firm growth and innovation strategies (Autio et al., 2014). The heterogeneity of sectoral technologies distinguishes the types of sectoral firms and innovation strategies. The ASOs in this study are specialised in five technology domains (i.e., digital, material technology/nanotechnology, biotechnology/chemical, energy/environmental, and maritime).

Product versus *process innovation* is frequently used to measure innovation in prior studies (De Jong and Marsili, 2006; Tether and Tajar, 2008; Peneder, 2010; Pavitt, 1984). Process innovation refers to direct or indirect new or substantially improved methods and inputs (i.e. equipment, software, and techniques) for the production and delivery processes within or between firms (OECD, 2005). Product innovation refers to new or significantly improved goods and services offered to end-users (OECD, 2005).

Basic versus *applied research* reflects the nature of research inputs for the innovation. Scientific research in academic institutions is the main source of knowledge input for ASOs in high-tech industries, such as ICT, biotechnology, nanotechnology, chemicals, and energy (Pavitt, 1984). Basic research seeks to understand a phenomenon or theory without considering particular applications, whereas applied research produces scientific knowledge for specific practical objectives or applications (Lim, 2004; OECD, 2015).

Academic institution indicates the parent organisation of an ASO. ASOs are usually originating from a university, but a significant share of academic research is performed by public research institutes. The latter institutes have no teaching obligations and are often conducting more applied research in collaboration with industry (Gulbrandsen, 2011). The types of CE innovations commercialized by ASOs may depend on the type of academic institution it comes from (i.e. university or public research institute).

Industry partnership relates to whether an ASO was set up in collaboration with an industrial partner. ASOs established as joint ventures with industry are regarded as being better in overcoming major development milestones (Munari and Toschi, 2011; Wright et al., 2004). This is because they are better at recognizing market opportunities, building legitimacy, and accessing critical resources and capabilities. Some CE strategies, particularly at the *meso* level, require higher between-firm collaborations to facilitate reuse of materials and by-product exchanges (de Jesus et al., 2018).

Patent is an indirect indicator of innovation that represents new technologies (Dziallas and Blind, 2019). Patents are considered a relatively reliable measurement of innovation activity (Acs et al., 2002), despite some limitations. For example, not all innovations are patented; patenting propensity depends on firms' innovation orientation such as product versus process, sector, and firm size; and inventions or radical innovations are more likely to be patented (Arundel and Kabla, 1998). Technology-based firms, such as ASOs, generally have a high patenting rate (Audretsch, 2002; Rydehell et al., 2019). Patenting among ASOs may also be associated with institutional, regional and organisational factors at the research organisation (Ar et al, 2021; Temel et al., 2021).

3.2.2. CE variables

CE strategies reflect the main strategies to enable a CE. The reduce strategy is used to minimise energy consumption, resource use, and waste emissions. The recover strategy means incinerating and converting residuals of unrecyclable waste into energy. The extend product longevity strategy through product designs and biochemical effects is often not explicitly mentioned in the four R framework but it is an essential CE strategy, especially for the biogeochemical cycle (Bocken et al., 2016). The recycle strategy involves the processing to extract secondary material from used waste materials or goods. The reuse strategy involves the second or further use of waste materials or products. This strategy can be grouped with the recycle strategy in the *closing the loop* principle (Bocken et al., 2016) when it indicates the reuse of waste materials from one process or one industry to another one. Moreover, the reuse strategy can be grouped with the extend product longevity strategy in *slowing the loop* principle (Bocken and Ritala, 2022) when it indicates the reuse of second-hand products. We grouped recycle and reuse into one variable category (recycle/reuse) because only a few companies belonged to the reuse and recycle categories. Moreover, the ASOs are engaged in reusing of waste materials, not second-hand products. Hence, in our context, the reuse strategy has closer meaning with the recycle strategy than the extend product longevity strategy.

Circular business models relate to the models that ASOs can adopt to commercialize CE innovations. Circular business models define how firms structure, innovate, and create value by narrowing, slowing, and closing the production-consumption loop. To measure different types of circular business models, we relied on the ReSOLVE framework proposed by the Ellen MacArthur Foundation (2015). Rosa et al. (2019) highlighted the simplicity but comprehensiveness of the ReSOLVE framework, which has become widely used to classify circular business models (Mendoza et al., 2017; De Angelis and Feola, 2020; Jabbour et al., 2019). This framework relates to six distinct circular business models (i.e., regenerate, share, optimize, loop, virtual, and exchange) (see Table 3). It is important to note that some firms may combine several circular business models simultaneously (Henry et al., 2020). During the coding, we found only the regenerate, optimize, loop, and virtual models among the ASOs. Therefore, the share and exchange models are not included in our analysis.

3.3. Multiple correspondence analysis

MCA with agglomerative hierarchical clustering was employed to generate a classification of CE-related ASOs based on CE innovations. MCA is a multivariate unsupervised learning method commonly used for exploratory, inductive research to explore new patterns in data, as well as to conduct quantitative predictions and construct taxonomies rather than deductive research and hypothesis testing (Greenacre and Blasius, 2006; Hoffman and De Leeuw, 1992; Clausen, 1998). MCA is not restricted by small samples and qualitative survey data and is

Table 3
The ReSOLVE framework.

CE business models	Objectives
Regenerate	Shifting to renewable energy and materials, restoring the ecosystem, or returning recovered biological resources back to the biosphere.
Share	Sharing ownership and asset.
Optimize	Increasing production efficiency to reduce waste and reduce resource consumption.
Virtual	Dematerialising physical objects and offering virtual products or services.
Loop	Circulating the resource flow by extending product longevity, recycling, and reusing materials and products.
Exchange	Radically shifting the production-consumption paradigm through disruptive technologies, such as 3D printing.

Source: Ellen MacArthur Foundation (2015) increasingly being used in a broad range of management and innovation studies (e.g., Parchomenko et al. (2019), Albats et al. (2022), Tether and Tajar (2008)). MCA can be useful for early-phase research fields, such as the CE field, that are characterised by limited theory development and small sample sizes.

MCA is conceptually analogous to principal components analysis (Greenacre and Blasius, 2006). However, MCA focuses on categorical variables on the same response scales instead of continuous variables (Greenacre, 2017). No prior hypothesis or distributional assumptions are required to apply this method. This is because MCA measures similarities between objects (i.e. ASO cases in rows and variables in columns) (Hoffman and De Leeuw, 1992). MCA provides solutions with multiple dimensions and produces a low-dimensional solution (i.e., often a two-dimensional plot) by assessing weighted least-square distance to identify the closet plane to the centre, and visualizing the points on the plane for interpretation (Di Franco, 2016; Greenacre, 2017). The MCA low-dimensional plot should include only the most important dimensions (i.e., the numbers of axes), based on the inertia percentage and the interpretability of the dimensions (Hoffmann, 1982). By applying MCA, we can uncover the relationships between variables (i.e., columns), the relationships between ASO cases (i.e., rows), and the relationships between variables and ASOs (Greenacre and Hastie, 1987).

To complement the MCA, we used agglomerative hierarchical clustering to elucidate the profiles of the ASO classification. Agglomerative hierarchical clustering is an algorithm that merges each pair of ASOs based on their nearest similarity distances and builds a dendrogram tree relating to the clustering (Jain et al., 1999; Bouguettaya et al., 2015). This technique enables researchers to identify nested partitions and draw contours around clusters on the MCA plot. Due to the categorical nature of our data, the cluster analysis relates to simple matching coefficients rather than regular Euclidean distances (Gower, 1971; Šulc and Řezanková, 2019). The open-source statistical software packages 'nonclust' (Sulc et al., 2020) and 'ca' (Nenadic and Greenacre, 2007) from the R environment were used.

MCA assesses the proximity between variables and between variables and the cases (i.e., ASOs) to examine the associations between them. The first interpretation of the MCA plot can be based on the proximity of the variables to the centre (i.e. origin point). Each variable and case is displayed as a coordinate point on the MCA low-dimensional plot (Greenacre and Hastie, 1987; Greenacre, 2017). The further a variable or a case locates from the centre, the higher variation of the objects is compared with the object's average patterns (Greenacre, 2017; Di Franco, 2016). It means that variables or cases situated further away from the centre are likely to have more distinctive, unique characteristics compared to the others. Conversely, variables or cases located near the centre have characteristics closer to the average pattern of the categories or appear more often in the dataset. The second important interpretation of the MCA plot relates to the distance between the variables, which shows to what extent the variables can be related. Closer proximity between variables or between cases suggests a higher degree of association between them or that they have similar characteristics (Greenacre, 2017; Di Franco, 2016).

4. Results

4.1. Characteristics of CE innovations commercialized by ASOs

To identify the types of CE innovations commercialized by ASOs, we used MCA to plot potential relationships between innovation and CE variables as shown in Fig. 3. The first dimension along the horizontal axis relates to the CE strategies of reduce, recover, recycle/reuse, and extend product longevity. The four CE strategies are distributed from left to right, also reflecting the principles of narrowing (i.e., reduce), slowing (i.e., extend product longevity), and closing (i.e., recover, recycle/reuse) the production-consumption loop. This dimension yielded 37 % of total inertia. The second dimension along the vertical axis differentiates

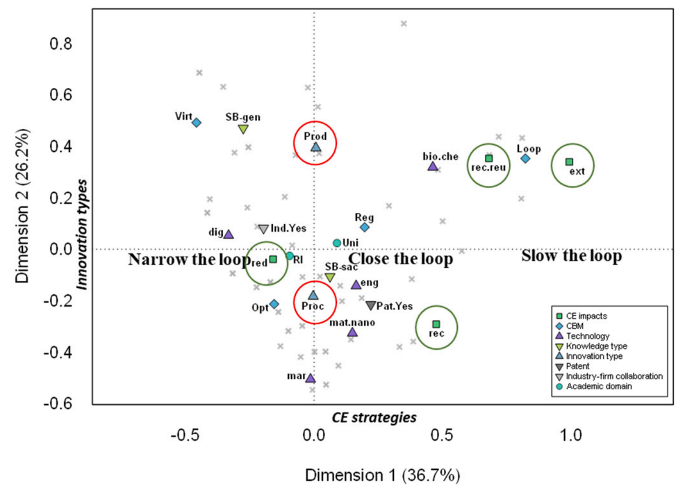

Fig. 3. MCA plot of the variables along the two dimensions of innovation types and CE strategies.

between product innovation located above the horizontal axis and process innovation located below. This dimension yielded 26 % of total inertia. Adding the third dimension increased the total inertia by only 10 %. A two-dimensional solution was therefore employed.

The MCA plot shows that the variables reduce, industry partnership, optimize, regenerate, university, research institute, digital technology, and energy/environment technology appear more frequently in the dataset and are therefore located close to the centre of the plot. These variables have values that are relatively similar to the average value of their variable categories. In contrast, the variables virtual, basic research, maritime technology, biochemical technology, recycle/reuse, loop, and extend product longevity, that are located further away from the centre, appear less frequently or seem to have more distinctive attributes.

Regarding the CE strategies, the MCA plot shows that the reduce strategy relating to *narrowing the loop* concerns both product and process innovations, and is most related to the optimize model, digital technology, industry collaboration, and research institutes. The digital technology variable is situated between the virtual and optimizes model variables as well as between the product and process innovation variables. This suggests that digital technology may be widely applicable for both product and process innovations in the virtual and optimize models. However, the virtual model is more likely to involve product innovations, whereas the optimize model is more likely to involve process innovations. Notably, the virtual model variable is close to the basic research and product innovation variables.

The recycle/reuse and extend product longevity strategies for *slowing the loop* tend to be associated with the loop model and biotechnology/chemical technology. They are situated on the upper right quadrant of the plot, and far from the other variables. This group of variables is linked more to product than process innovations. ASOs commercializing CE innovations related to biotechnology/chemical technology tend to adopt the loop model and introduce product innovations for extending product longevity, recycling, and reusing products and materials.

The recover strategy for closing the product-consumption loop is more likely to be associated with process innovations. This CE strategy is related to the material technology/nanotechnology, energy/environmental technology, applied research, and patent variables. The energy/environmental and material science/nanotechnology variables are located close to each other. This closeness suggests that these technologies can be used to achieve the same CE strategy. Conversely, the variables digital technology and biochemical technology are located at the opposite ends of the plot.

4.2. Constructing the clusters of CE-related ASOs

Using MCA and agglomerative hierarchical clustering analysis we constructed a taxonomy of five distinct types of CE-related ASOs: smart product-service providers, technical process enhancers, biochemical cycle extenders, renewables providers, and biosphere regenerators. These five clusters were positioned along two dimensions relating to the innovation types (i.e., product versus process innovations), and the CE principles (i.e., narrowing, slowing, and closing the production-consumption loop) as visualised on the MCA plot in Fig. 4. A profile of each cluster including the innovation and CE variables in percentages is presented in Table 4. Table 5 summarises the five clusters and their main innovation and CE attributes.

4.2.1. Cluster 1: the smart product-service provider

Cluster 1 is labelled ‘smart product-service providers’ and relates to 8 ASOs offering virtual products and services. The location on the upper left quadrant of the MCA plot and far from the other clusters suggests that Cluster 1 has distinct characteristics compared to the other four clusters. The ASOs in this cluster focus on the *narrowing the loop* principle, use only digital technologies, and are strongly associated with the reduce strategy. These ASOs adopt the virtual model to deliver digital artefacts and digital platforms for substituting or dematerialising physical products to simultaneously increase resource efficiency and reduce costs, resource consumption, and waste. All CE innovations in this cluster are product-oriented. Several CE innovations of this cluster are relatable to the collaborative or access-based consumption of the ‘sharing economy’ concept (Sánchez-Pérez et al., 2021). For example, e-learning courses increase virtual collaborations between users and reduce the use of materials for paper books, transportation, and logistics related to organising physical teaching. Another example is the virtual laboratories that minimise prototype waste, resource use, and energy consumption. Further, these CE innovations make not only environmental impacts but also economic impacts by helping reduce the unit costs of collaborating, training, and developing products and services. The CE innovations in this cluster derive from both applied and basic research mostly by universities. None of the firms in this cluster patent their digital CE innovations.

4.2.2. Cluster 2: technical process enhancer

Cluster 2 is labelled ‘technical process enhancers’ and relates to 35 ASOs commercializing CE innovations to increase productivity and efficiency. This cluster is centrally located on the MCA plot. The ASOs also focus on the *narrowing the loop* principle and exploit technological advances relating to different types of technologies to improve production performances (i.e., oil drilling, fish farming, or energy generation). The ASOs in this cluster typically use process innovations (94 %) to reduce the consumption of natural resources and energy, as well as to reduce waste emissions. For this cluster, digital technologies (e.g., cyber-physical systems integrating real-time data, sensors, simulation, and robotics) are the key enabler to achieve resource efficiency, optimize production performance, reduce shutdown time, decrease resource inputs, and lower carbon dioxide output. The CE process innovations of Cluster 2 rely heavily on applied research and are more often created by research institutes than universities. About half of the CE innovations in Cluster 2 are patented and most ASOs have industry partnerships. The largest subgroups of ASOs in this cluster relate to the oil/gas/offshore sector and the maritime/aquaculture sector.

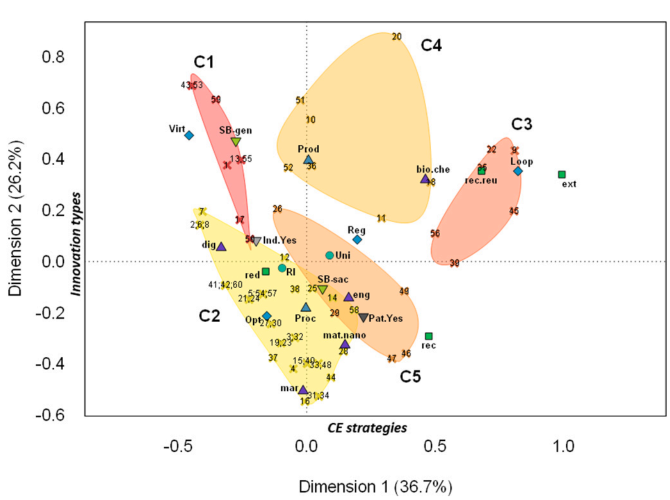

Fig. 4. The five clusters (C1–C5) visualised on the MCA plot.

4.2.3. Cluster 3: biochemical cycle extender

Cluster 3 is labelled ‘biochemical cycle extenders’ and relates to 6 ASOs commercializing innovations to extend the biochemical lifecycle of materials and products. This cluster is situated on the right periphery of the MCA plot, quite far from the centre and near Cluster 2 and Cluster 4 but opposite Cluster 1. The ASOs in this cluster focus on the *slowing the loop* principle and exploit technologies (i.e. biotechnology/chemical technology or material technology/nanotechnology) that keep materials and products in longer, recursive use and revive end-of-use products and materials for a second life. This cluster engages in the recycle and reuse, and the extend product longevity strategies. The ASOs contribute to reducing biomass waste. Cluster 3 ASOs commercialize both product innovations (i.e. new instruments or substances) and process innovations (i.e. new logistics or production methods) and adopt the loop model. The CE innovations tend to be based on applied research by universities and often include patented technologies. None of the ASOs are established with industry partnership.

4.2.4. Cluster 4: renewables provider

Cluster 4 is labelled ‘renewables provides’ and relates to 5 ASOs commercializing innovations to shift to renewable materials and products. This cluster is located in the upper-middle space of the MCA plot. The ASOs focus on the *closing the loop* principle and produce biomaterials, biofuels, bioenergy, bio proteins, sustainable chemicals, and pharmaceuticals to replace the use of fossil fuels and the extraction of finite natural resources. Moreover, the ASOs optimize the use of renewable natural resources, for example, microalgae, aquatic plants, and microorganisms, and recycle natural gas and carbon dioxide to create values of renewable ingredients and energy inputs. They rely primarily on biotechnology/chemical technology and energy/environmental technology to transform from a fossil-based to a more circular, bio-based economy. Their CE strategies are reduce, recycle, and reuse to be adopted in the regenerate model in various sectors progressing a shift towards biomaterial consumption. Their CE innovations tend to introduce CE product innovations and are based on basic research. Their parent organisations are often research institutes. They report lower rates of patented innovations but higher rates of industry collaboration compared to firms in Cluster 3.

4.2.5. Cluster 5: biosphere regenerator

Cluster 5 is labelled ‘biosphere regenerators’ and relates to 6 ASOs commercializing innovations to convert non-recyclable waste into energy and resources through by-product exchange between actors in a production system and make material flow regenerative. This cluster is located in the lower space of the MCA plot near Cluster 2. The ASOs focus on the *closing the loop* principle and relate to the recover and reduce strategies and the regenerate model. Energy technology is the primary technology in this cluster, together with biotechnology/chemical technology. Cluster 4 ASOs are involved in industrial symbiosis, whereby the wastes from one firm become valuable resources for another firm. They have the highest patent rate and the highest rate of industry partnerships. Further, Cluster 5 ASOs are more inclined to

Table 4
Cluster profiles with the percentages of innovation and CE variables in each cluster.

Variable	Description	Total	Cluster 1 (8 firms)	Cluster 2 (35 firms)	Cluster 3 (6 firms)	Cluster 4 (5 firms)	Cluster 5 (6 firms)
Dig	CE innovations related to digital technology	43.33 %	**100.00 %** (56.67 %)	**52.94 %** (9.61 %)	0.00 % (−43.33 %)	0.00 % (−43.33 %)	0.00 % (−43.33 %)
Mat.nano	CE innovations related to material technology or nanotechnology	10.00 %	0.00 % (−10.00 %)	14.71 % (4.71 %)	16.67 % (6.67 %)	0.00 % (−10.00 %)	0.00 % (−10.00 %)
Bio.che	CE innovations related to bio technology or chemical technology	21.67 %	0.00 % (−21.67 %)	5.88 % (−15.78 %)	**66.67 %** (45.00 %)	**85.71 %** (64.05 %)	20.00 % (−1.67 %)
Eng	CE innovations related to energy or environmental technology	18.33 %	0.00 % (−18.33 %)	14.71 % (−3.63 %)	16.67 % (−1.67 %)	14.29 % (−4.05 %)	**80.00 %** (61.67 %)
Mar	CE innovations related to maritime technology	6.67 %	0.00 % (−6.67 %)	11.76 % (5.10 %)	0.00 % (−6.67 %)	0.00 % (−6.67 %)	0.00 % (−6.67 %)
Prod	CE product innovations	31.67 %	**100.00 %** (68.33 %)	5.88 % (−25.78 %)	**33.33 %** (1.67 %)	**100.00 %** (68.33 %)	0.00 % (−31.67 %)
Proc	CE process innovations	68.33 %	0.00 % (−68.33 %)	**94.12 %** (25.78 %)	**66.67 %** (−1.67 %)	0.00 % (−68.33 %)	**100.00 %** (31.67 %)
SB-gen	CE innovations based on basic research	18.33 %	**37.50 %** (19.17 %)	8.82 % (−9.51 %)	0.00 % (−18.33 %)	**57.14 %** (38.81 %)	20.00 % (1.67 %)
SB-SAC	CE innovations based on applied research	81.67 %	**62.50 %** (−19.17 %)	**91.18 %** (9.51 %)	**100.00 %** (18.33 %)	42.86 % (−38.81 %)	**80.00 %** (−1.67 %)
RI	CE-related ASOs originated by research institutes	48.33 %	25.00 % (−23.33 %)	**58.82 %** (10.49 %)	16.67 % (−31.67 %)	**71.43 %** (23.10 %)	20.00 % (−28.33 %)
Uni	CE-related ASOs originated by universities	51.67 %	**75.00 %** (23.33 %)	41.18 % (−10.49 %)	**83.33 %** (31.67 %)	28.57 % (−23.10 %)	**80.00 %** (28.33 %)
Ind	CE innovations that involves Industry partnership	38.33 %	37.50 % (−0.83 %)	41.18 % (2.84 %)	**0.00 %** (−38.33 %)	42.86 % (4.52 %)	**60.00 %** (21.67 %)
Pat	CE innovations that was patented	48.33 %	**0.00 %** (−48.33 %)	55.88 % (7.55 %)	66.67 % (18.33 %)	**28.57 %** (−19.76 %)	**80.00 %** (31.67 %)
Red	CE innovations related to reduce strategy	81.67 %	**100.00 %** (18.33 %)	**100.00 %** (18.33 %)	0.00 % (−81.67 %)	**71.43 %** (−10.24 %)	40.00 % (−41.67 %)
Rec	CE innovations related to recover strategy	5.00 %	0.00 % (−5.00 %)	0.00 % (−5.00 %)	0.00 % (−5.00 %)	0.00 % (−5.00 %)	**60.00 %** (55.00 %)
Ext	CE innovations related to ‘extend product longevity’ strategy	5.00 %	0.00 % (−5.00 %)	0.00 % (−5.00 %)	**50.00 %** (45.00 %)	0.00 % (−5.00 %)	0.00 % (−5.00 %)
Rec.reu	CE innovations related to recycle and reuse strategy	8.33 %	0.00 % (−8.33 %)	0.00 % (−8.33 %)	**50.00 %** (41.67 %)	**28.57 %** (20.24 %)	0.00 % (−8.33 %)
Opt	CE innovations related to ‘optimize’ circular business model	55.00 %	25.00 % (−30.00 %)	**91.18 %** (36.18 %)	0.00 % (−55.00 %)	0.00 % (−55.00 %)	0.00 % (−55.00 %)
Virt	CE innovations related to ‘virtual’ circular business model	11.67 %	**75.00 %** (63.33 %)	2.94 % (−8.73 %)	0.00 % (−11.67 %)	0.00 % (−11.67 %)	0.00 % (−11.67 %)
Loop	CE innovations related to ‘loop’ circular business model	11.67 %	0.00 % (−11.67 %)	0.00 % (−11.67 %)	**100.00 %** (88.33 %)	14.29 % (2.62 %)	0.00 % (−11.67 %)
Reg	CE innovations related to ‘regenerate’ circular business model	21.67 %	0.00 % (−21.67 %)	5.88 % (−15.78 %)	0.00 % (−21.67 %)	**85.71 %** (64.05 %)	**100.00 %** (78.33 %)

The significant percentages of dominant clusters in each CE innovation attribute.

Table 5
Taxonomy of ASOs pursuing CE innovations.

CE principles Innovation	Narrow the loop (reduce)	Slow the loop (extend, reuse)	Close the loop (recycle, recover)
Product innovations	CLUSTER 1: SMART PRODUCT-SERVICE PROVIDER Offering virtual products and services • Product innovations • Virtual (dematerialise) • Reduce resource consumption and waste • General knowledge • No patent rate	CLUSTER 3: BIOCHEMICAL CYCLE EXTENDER Extending the biochemical lifecycle of materials and products • Product innovations • Process innovations • Loop (extend lifecycle) • Extend product/material longevity, reuse, recycle • Applied knowledge • High patent rate	CLUSTER 4: RENEWABLES PROVIDER Shifting to sustainable renewable materials and products • Product innovations • Regenerate (shift to renewable energy/resources) • Reduce resource consumption, recycle, reuse • General knowledge • Low patent rate
Process innovations	CLUSTER 2: TECHNICAL PROCESS ENHANCER Increasing productivity and efficiency • Process innovations • Optimize (enhance production process) • Reduce resource consumption and waste • Applied knowledge • High patent rate		CLUSTER 5: BIOSPHERE REGENERATOR Converting non - recyclables into energy and resources • Process innovations • Regenerate (convert non-recyclable waste into resources) • Reduce resource consumption, recover • Applied knowledge • Very high patent rate

commercialize process innovations that are based on applied research and they originate mostly from universities.

5. Discussion

More than half of the CE-related ASOs belong to Cluster 2 'technical process enhancers'. Accordingly, the majority of CE innovations involve the *narrowing the loop* principle, the reduce strategy (81 %), and the optimize model (55 %). This empirical evidence appear contrary to several studies suggesting that the *closing the loop* principle and the recycle strategy are dominant among firms initiating CE efforts (Ghisellini et al., 2016; Merli et al., 2018). However, this difference may be related to the sample of ASOs in this study. Hence, our findings confirm the claims of Henry et al. (2020), Parchomenko et al. (2019), and Merli et al. (2018) that CE innovations introduced by new entrants are mostly related to the reduce strategy to optimize resource efficiency and minimise waste residues. This also aligns with other studies finding that many firms focus on technical solutions to achieve resource efficiency and production circularity (Rajput and Singh, 2019).

CE innovations relating to the reduce strategy, the optimize model, and digital technologies seem like an attractive basis for establishing ASOs. The improvements in productivity and efficiency from these innovations could result in clear economic gains, such as reducing raw material and energy costs by minimising resource scarcities, reducing value loss through waste, and paving the paths for new markets by retaining the value of goods and materials (Korhonen et al., 2018; Lieder and Rashid, 2016). Thus, resource efficiency and production optimization through highly innovative technologies and the reduce CE strategy could be more prevalent among new firms with fewer resources, while the recycle and reuse strategies are more relevant to large firms with structural inertia that add incremental CE innovations to their existing business models. The divergence in the CE strategies of large firms versus small and start-up firms underscores the value of developing taxonomies for specific types of firms.

ASOs commercialize CE innovations related to both the biological and technical cycles (Leipold and Petit-Boix, 2018), but predominantly in the technical cycle. Cluster 1 'smart product-service providers' and Cluster 2 'technical process enhancers' are both related to the technical cycle to improve cleaner production and reduce the amount of waste residual and resource use. The main difference between these two clusters is that Cluster 1 focuses on downstream activities with product-service innovations on the consumption side, while Cluster 2 focuses on upstream activities with process innovations on the production side. Cluster 1 and Cluster 2 can together generate combinatory effects on the technical side of the production-consumption system. Digital technology is dominant among ASOs in Cluster 1 and Cluster 2. The smart product-service providers focus on developing digital artefacts and platforms (i.e. new configuration, features, digital products, and services) through the virtual model to deliver products and services to end-user consumers. The technical process enhancers provide digital infrastructure (i.e. the Internet of Things, automation, sensors) through the optimize model to improve manufacturing and logistics processes.

The biogeochemical cycle and the CE are tightly intertwined (Leipold and Petit-Boix, 2018). We found that the CE innovations of Cluster 3 'biochemical cycle extenders', Cluster 4 'renewables providers', and Cluster 5 'biosphere regenerators' are related to the biogeochemical cycle. These innovations entail recycling and converting residuals into inputs and energy, thereby replacing crude-oil substances with bio-based substances or extending product longevity. Although ASOs in both Cluster 3 and Cluster 4 relate to the same biogeochemical cycle, their business activities and CE principles are largely different. Cluster 3 relates to the *slowing the loop* principle, and entails the loop model to extend product longevity and bring second lives to materials and products. Cluster 4 relates to the *closing the loop* principle and entails the regenerate model of shifting towards biomaterial uses. Cluster 3 uses biotechnology/chemical technology and entails the loop model to enhance the quality and extend the longevity of organic products. The CE literature shows that the product-service system (also called servitised model) can also be used to extend the longevity of technical products by sharing ownership and reusing products (Tukker, 2015). However, Cluster 3 firms did not engage in activities extending the lifecycle of technical products. This may be because ASOs tend to be high-technology firms rather than service-based firms.

Cluster 5 uses the same regenerate model as Cluster 4, but their innovations relate to different CE strategies. Cluster 5 captures the value loss of non-recyclable items by converting residual outputs of one production process into new forms of energy resources or inputs to another production process. Conversely, Cluster 4 focuses on sustainable product designs and replacing non-renewable with renewable resources by using, reusing, and recycling abundant natural materials. Consequently, the technologies of Cluster 4 and Cluster 5 are also dissimilar, as the renewables providers exploit biotechnology/chemical technology, while the biosphere regenerators use energy technology/environmental technology.

In terms of the CE benefits from the interactions among actors (Ghisellini et al., 2016), CE innovations of the ASOs may entail industrial symbioses and firm partnerships to supply and transfer technologies from one firm to another (i.e., Clusters 1 and Cluster 2 relating to the *narrowing the loop* principle), or to facilitate the exchanges of CE materials and products between firms (i.e., Cluster 4 and Cluster 5 relating to the *closing the loop* principle). We found that industrial symbiosis is particularly important to Cluster 4 and Cluster 5 that facilitate resource exchanges and by-product utilisations among organisations in a network to retain residual value in the 'take-back' system and replace non-renewable with renewable material inputs (Ghisellini et al., 2016). Value retention can focus on retaining the value of recyclable materials and products (i.e., the recycle strategy) or the value of non-recyclable materials by converting them into other types of resources, such as waste into energy (i.e., the recover strategy). Finally, both Cluster 5 and Cluster 2 create process innovations to reduce resource inputs and waste outputs. Although the results are similar, their processes differ. While Cluster 2 reduces consumption by increasing production efficiency, Cluster 5 regenerates non-recyclable waste into energy to minimise new resource extraction.

6. Conclusions and implications

This study examines the potential roles of innovative start-ups, such as ASOs, in commercializing science-based innovations with potential CE impacts. Our results indicate that ASOs play an important role in converting scientific knowledge and radical innovations into applications that facilitates the CE transition of narrowing, slowing, and closing the production-consumption loop. By developing a taxonomy based on innovation and CE characteristics, our study provides three key contributions.

First, by focusing on technology supply, this taxonomy adds an important dimension to the growing CE literature which has predominantly considered the role of policy regulations and market demand (Cainelli et al., 2020). A relatively large share of the ASOs in our sample pursued CE-related innovations and our taxonomy shows that the ASOs rely on different types of CE principles and commercialize both product and process innovations. The technologies developed by ASOs can be a significant source of CE innovations. The largest cluster of CE-related ASOs is Cluster 2, the 'technical process enhancers', which develop technologies that optimize production processes and thereby reduce resource consumption and waste by narrowing the production-consumption loop. It shows that most ASOs do not primarily introduce new CE-oriented products and services, but play an important role in helping to optimize existing industrial processes. In addition, the most frequently used CE strategy was the reduce strategy, used by 81 % of the ASOs, followed by the recycle and reuse strategies at 8 % each. This result aligns with the findings of Henry et al. (2020) and Parchomenko et al. (2019) that reduce, recycle, and reuse are the most adopted CE strategies. By mainly contributing through the principle of narrowing the production-consumption loop, the ASOs are likely to provide innovations that make processes in larger firms more effective, rather than developing new products and services. Thus, partnering with ASOs may be an efficient strategy for larger organisations to respond to regulations and demand changes that require innovations towards a more CE.

Second, by using CE contributions to classify ASOs, our taxonomy of innovative firms adds to existing innovation taxonomies relating to the firm- and industry-level characteristics (Libaers et al., 2016; De Jong and Marsili, 2006). This adds to existing taxonomies that mainly relied on data from larger and more established firms (De Marchi et al., 1996; Pavitt, 1984). Our empirical evidence provides a foundation to better understand the development paths of innovative start-ups and shows that Pavitt (1984)'s taxonomy should be extended with more detailed taxonomies showing the diversity of small innovative firms in general (Libaers et al., 2016) and science-based firms in particular. Furthermore, the addition of the CE context variables provides a groundwork for developing innovation taxonomies that conceptualize the potential role of innovation for sustainability transitions (Fagerberg, 2018). Adding the CE variables helps conceptualize the potential wider societal impacts of ASOs (Fini et al., 2018) and innovative start-ups in general (Audretsch et al., 2020). ASOs may introduce new technologies that are developed into circular business models, convert scientific knowledge into CE practices, and enable technological changes in their innovation ecosystem for higher levels of circularity.

Third, our findings add to the science commercialization and academic entrepreneurship literature by mapping specific ways that ASOs can provide societal impacts (Fini et al., 2018). Our taxonomy conceptualizes how ASOs can play an important systemic role in facilitating the conversion of new scientific inventions and knowledge into applications, for instance by optimizing industrial processes (Autio, 1997). This role may be particularly crucial for facilitating CE-related innovations that often require extensive collaboration between actors across the value chain (de Jesus et al., 2018). Radical innovations may be required to reform new customer value propositions in a CE (Ranta et al., 2020) and ASOs may play a particularly important role in developing such innovations. Hence, ASOs may be in a unique position to provide innovations that facilitate for example industrial symbioses or other improvements to make industrial processes more circular. Understanding the potentially unique roles of different types of firms in developing CE innovations, and in the 'circular ecosystems' (Konietzko et al., 2020), is crucial for achieving CE targets. Our taxonomy takes an important step in this regard.

6.1. Implications for practice and policy

Our findings provide implications for managers and policymakers regarding the role of innovative start-ups in facilitating the transition to a stronger CE. A new wave of innovation policies aiming for system-wide transformation referred to as the Innovation Policy 3.0 frame (Grillitsch et al., 2019), calls for policies that include the objective of contributing to the sustainability transition. ASOs can potentially introduce CE innovations that are more radical than those developed by large firms. Our taxonomy of five distinct types of CE-related ASOs can help design more targeted policies and customized supports. In particular, the role of ASOs in optimizing industrial processes shows the importance of considering their CE contribution not only at the firm level but also in terms of the firm being an ecosystem actor. Hence, promoting the creation and development of ASOs that commercialize CE innovations may be an important part of the policy mix for the sustainability transition (Kivimaa and Kern, 2016). More policy supports should be established to foster collaborative synergies, reinforce networks, and build capabilities for the actors such as CE ASOs and their partners in CE entrepreneurial ecosystems (Ferreira and Dabic, 2022). Furthermore, our empirical evidence on the significant initiatives of CE ASOs also suggests more entrepreneurship education focusing on CE could be provided at academic institutions to increase the value creation of CE entrepreneurship (Del Vecchio et al., 2021).

Our taxonomy adds to the understanding of the roles played by different types of CE-related ASOs, as the societal impacts and the contributions to more sustainable development are gaining strong attention. ASOs can contribute to a more CE in several ways using different CE principles and types of CE innovations. Our empirical evidence shows relevance and consistency with the EU's Circular Economy Action Plan 2020 which emphasized digital technologies, resource efficiency, and entrepreneurial firms as key enablers of the CE transition. "Building on the single market and the potential of digital technologies, the circular economy can strengthen the EU's industrial base and foster business creation and entrepreneurship among SMEs" (the EU's Circular Economy Action Plan 2020, p.2). The significant role of digital technologies can be seen in the dominance of the two largest clusters of ASOs (Cluster 1 'smart product-service provider' with 8 ASOs and Cluster 2 'technical process enhancer' with 35 ASOs) to narrow the loop by adopting the reduce strategy. Digital technologies are crucial to facilitate the virtual products and services of Cluster 1 and improve the production resource efficiency of Cluster 2 to minimise resource consumption and waste emissions.

Critics have questioned whether the narrow the loop principle by optimizing production processes is sufficient for a CE transition (Bocken et al., 2016). The EU's Circular Economy Action Plan 2020 (p.12) reported that "despite efforts at EU and national level, the amount of waste generated is not going down" and that more efforts of recycling and reuse are needed. Optimizing the production process may lead to the use of fewer resources, but is essentially the same as a resource efficiency strategy used in the linear economy. Hence, if the resource efficiency gained by these innovations is used to increase production output by using the same amount of resources, there is no shift to a CE. To make sure the innovations provide a real CE contribution, the time dimension has to be addressed. Otherwise, a high share of the ASOs in our sample (i.e. Cluster 2) may not only narrow the production-consumption loop but also speed up the loop. Hence, the narrow the loop principle is likely to have a stronger impact if combined with principles to slow and close the production-consumption loop.

To increase more slowing and closing of the production-consumption loop, more policy incentives should also be focused on Cluster 3 'biochemical cycle extender' to slow the rate of waste emission and Cluster 5 'biosphere regenerator' to reduce the waste amount (e.g., burn to convert into energy or be the inputs for other production processes). As mentioned in Section 2.3 of the EU Circular Economy Action Plan 2020 as well as explained by our taxonomy, industrial symbiosis is vital to enable circularity in the production processes, especially those belonging to the biochemical cycles. Therefore, stronger systems of industrial symbiosis should be reinforced to enable and facilitate the CE innovations of Cluster 4 and Cluster 5.

6.2. Limitations and directions for additional research

This study comes with several limitations and associated directions for further research. First, we relied on an extensive media search to identify CE-related activities and events in ASOs. However, some activities and events likely went unnoticed by the media, leading to an under-reporting of cases. We attempted to minimise underreported cases by combining media data with other data sources, such as company websites, financial data, and firms' history and legal data. Further studies may use other types of data to complement our results, such as survey data and patent data, but these data sources also face distinct weaknesses.

Second, the MCA method unveils the relatedness patterns of variables and cases but does not confirm the significance of these relationships. We reveal several patterns of CE ASOs that call for further investigations. For example, we observed that the product CE innovations occurring in Cluster 4 tend to be based more on basic research and general knowledge than innovations occurring in other clusters. The waste-to-energy conversion innovations that were frequent in Cluster 5 were associated with a higher patent rate compared to the digital product innovations of Cluster 1 and the biochemical product innovations of Cluster 5. Some clusters have a higher likelihood of industry partnerships than others. Additional studies are warranted to explore why and how these patterns arise. Multivariate regression analysis is required to validate and test the emergent patterns reported in our study.

Third, our study mapped the activities of ASOs at a relatively early stage. Hence, we cannot assess whether some types of ASOs are more successful than others in terms of financial performance or survival. A promising line of enquiry would be to examine the performance implications for ASOs commercializing the distinct CE-related innovations in our taxonomy. Different types of ASOs likely follow distinct pathways to reach the market. For instance, Cluster 2 'technical process enhancers' may be more dependent on partnering with large firms to reap process benefits, while Cluster 1 'smart product-service providers' can scale their activities more independently. ASOs in the different clusters may develop and perform differently over time. For example, bio-based CE innovations may require more time for development and commercialization than digital CE innovations. Hence, our taxonomy may provide a starting point to examine these distinct development paths and their implications for both firm performance and the societal impacts of ASOs in terms of CE contributions.

Data availability

The data that has been used is confidential.

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