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Dynamic capabilities for circular manufacturing supply chains—Exploring the role of Industry 4.0 and resilience

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Abstract

An organisation's sustainability performance is influenced by its capabilities (skills, resources and competences) which in turn affects the performance of its entire supply chain. However, recent research has not sufficiently explored the convergence of dynamic capabilities, circular economy, resilience and Industry 4.0 concepts for manufacturing supply chains. Therefore, this study aims to identify how dynamic capabilities theory can enable circular and resilient supply chains. A qualitative research process was deployed in three stages: literature review, European project and nine expert interviews. Key investigative variables were used to identify capabilities used in manufacturing, and five research propositions were developed to address the gaps found in literature. The empirical data helped reveal challenges to circular economy implementation and validate the literature findings. The main contributions include a dynamic capabilities model, a causal relationship model and five research propositions for circular economy implementation.

KEYWORDS
circular economy, dynamic capabilities, industrial Symbiosis, Industry 4.0, resilience, supply chains

1 | INTRODUCTION

Manufacturing companies are under increasing pressure to become more sustainable (considering environmental, social and economic aspects), and we may be consuming resources 50% faster than the earth's replenishing capacity (Siegel et al., 2014). Industry, academia and other stakeholders need to collaborate and find solutions to rapidly adapt and mitigate these issues and decouple economic development from social and environmental impact.

The circular economy (CE) concept can help supply chains (SCs) transition from linear (‘take-make-dispose’) to circular modes of production and consumption and potentially reduce their environmental impact (Baldassarre et al., 2019; Graedel & Allenby, 2003). However, CE is increasingly challenging to incorporate into business models and operational practices due to high set-up costs, information availability

Abbreviations: CE, circular economy; DC, dynamic capability; DCV, Dynamic Capabilities View; I4.0, Industry 4.0; IS, Industrial symbiosis; SC, supply chain.

for design, changes required at various system levels and so on (Bag & Pretorius, 2020; Geissdoerfer et al., 2017; Ritzén & Sandström, 2017; Sousa-Zomer et al., 2018). Scholars have suggested that the development and implementation of 'dynamic capabilities' could help in the CE transition (Bocken & Geradts, 2020; Khan et al., 2020; Moon & Lee, 2021; Scarpellini et al., 2020; Shayganmehr et al., 2021).

Dynamic capabilities (DCs) have been referred to as a source of a firm's competitive advantage (Beske et al., 2014). Sustainability and CE challenges requires organisations to constantly adapt to changing environmental demands and develop eco-capabilities such as resilience (Souza et al., 2017). In addition, CE provides opportunities to improve material cost, reduce environmental impacts and improve SC resilience (Edwin Cheng et al., 2021; Jakhar et al., 2019).

Industrial symbiosis (IS) is a well-defined approach to CE, promoting waste and resource exchange between industrial companies. It has progressively developed in some regions of the world but has yet to become a more pervasive approach in manufacturing (Domenech et al., 2019). IS predates CE (Chertow, 2000; Ehrenfeld & Gertler, 1997) and specifically targets underutilised waste, by-products, logistics, expertise and equipment, thereby increasing resource productivity both within and beyond a single company's boundaries (Lombardi & Laybourn, 2012; Zheng & Jia, 2017).

The Fourth Industrial Revolution or Industry 4.0 (I4.0) presents opportunities to improve industrial performance sustainably (Kagermann, 2013; Kiel et al., 2017; Müller et al., 2018) and to support CE (Blunck & Werthmann, 2017; Chiappetta Jabbour et al., 2020; de Sousa Jabbour et al., 2018; Dev et al., 2020; Shayganmehr et al., 2021). For example, Machado et al. (2020) presented I4.0 as an enabler for sustainable manufacturing and discussed its inclusion in the global industry development and government agenda. Such government programmes include 'Factories of the Future (FoF)', a German initiative, which sets sustainable value networks based on circular strategies as one of its goals (Küpper et al., 2016). The Swedish programmes 'Smart Industry' and 'Produktion 2030' seek to develop sustainable and resource-efficient production, viewing digitalization as one of the strategies towards a fossil-free and circular model by 2030 (Ministry of Enterprise and Innovation, 2016; Teknikföretagen, 2017).

Along with resilience, the I4.0 paradigm can help organisations rapidly make decisions in changing dynamic environments (Valilai & Sodachi, 2020). Advances in I4.0 technologies—for example, digital twins, artificial intelligence, blockchain, virtual and augmented reality, big data analytics, 5G connectivity, additive manufacturing and smart sensors (Machado et al., 2020; Price Waterhouse Cooper, 2018)—can improve flexibility, transparency, productivity and resource efficiency and thereby improve the sustainability of SCs (Blunck & Werthmann, 2017; Chari et al., 2021; Pagoropoulos et al., 2017).

In addition, attaining organisational sustainability is possible by transitioning towards sustainable supply chain management practices (de Sousa Jabbour et al., 2019), which forms an integral part of CE (Bai et al., 2019; Genovese et al., 2017). Hence, to avoid adverse effects such as burden-shifting, sustainability needs to be incorporated from a more holistic end-to-end SC perspective.

The combined effects of resilience and sustainability concepts in manufacturing SCs are not well-defined and seen as fragmented (Gatenholm et al., 2021; Negri et al., 2021). However, these concepts could be linked using the dynamic capability view (DCV) in the context of CE. This approach can help organisations to proactively formulate environmental strategies bringing sustainable competitive advantage in dynamic environments.

Hence, previous studies on capabilities (i) have mainly focused on static capabilities in firms; (ii) do not largely include the SC network, with limited studies in the manufacturing sector; (iii) have not studied the combination of DCs and CE principles and how this can make organisations more resilient, to a large extent; and (iv) have not fully explored the role of I4.0 technologies and its operating principles—which is an emerging research agenda—to build the necessary DCs in manufacturing SCs.

The main research question that will be addressed in the paper is: How can dynamic capabilities enable manufacturing SCs to build resilience and transition to CE? Hence, the purpose of the paper is to identify the current challenges to collaborate and develop circular and resilient SCs and the role of I4.0 in the development of DCs. We contribute to theory at the convergence of these topics and provide industrial practitioners with a dynamic capabilities and causal relationship model, along with five research propositions.

The remainder of the paper is organized as follows: this section is followed by the theoretical background in Section 2. The research methodology is described in Section 3 followed by Section 4 which showcases the results in the form of challenges and capabilities for CE implementation, a DC model and causal relationship model. Section 5 discusses the development and validation of five research propositions along with the research quality, and Section 6 presents the conclusions.

2 | THEORETICAL BACKGROUND

In this section, we provide a theoretical background of DC theory, resilience for sustainability (particularly CE) and Industry 4.0 principles for CE (and IS) to gain an understanding of how the concepts are related and develop a conceptual framework to guide the research. The literature review also highlighted the research gaps, identified capabilities and provided a basis for the formulation of five research propositions.

2.1 | Dynamic capabilities (underpinning theory)

The adoption of CE comes with several challenges such as high uncertainty levels, production losses, excess inventories (Ritzén & Sandström, 2017), complex material and energy flows, data management, attitudes (Bag, Pretorius, et al., 2021) and so on. As mentioned earlier, researchers have suggested that DCs can allow organisations to respond to uncertainties and adopt circular practices (Moon & Lee, 2021; Scarpellini et al., 2018; Shayganmehr et al., 2021).

Capabilities are complex bundles of skills and knowledge and can be static (operational or organisational) (Benner, 2009; Collis, 1994) or dynamic.

The Dynamic Capabilities View (DCV) is an extension of the traditional Resource Based View (RBV) of organisations (Eisenhardt & Martin, 2000; Teece et al., 1997; Teece & Pisano, 1994), which evolves from existing resources and help organisations transition from static to dynamic/uncertain environments (Díaz-Chao et al., 2021). Whereas the RBV focuses on selection from existing resources, the DCV focuses on resource development, acquisition and exploitation (Edwin Cheng et al., 2021; Hong et al., 2018; Moon & Lee, 2021). Organisations should reconfigure their resources and capabilities to address challenges and changing environments to stay competitive.

While there are several conceptualisations of the DCV in literature, the most widespread is the one proposed by Teece and Pisano (1994) who explained that DCs determine how a firm integrates, builds and reconfigures internal and external competences to address changing business environments. These capabilities are unique to individual firms and their effectiveness are dependent on parameters existing within these firms. The 'dynamic' aspect refers to the changing environment caused by varying market conditions and the accelerating pace of innovation. 'Capabilities' refer to the 'sensing', 'seizing' and 'transforming' of internal and external skills, resources and competences to the constantly shifting environment. Sensing capabilities are the ones that allow companies to identify, develop and assess technological opportunities with regards to customer needs; seizing capabilities allow companies to mobilize resources to address anticipated market needs; and transforming capabilities allow the company to make the shift to more competitive business models (Teece, 2007; Teece et al., 2016; Teece & Pisano, 1994).

Moreover, the three types of capabilities are supported by enabling 'microfoundations' (Teece, 2007). Microfoundations are unique to specific organisations and help them achieve sustainable competitive advantage, making it challenging for their competitors to develop and deploy. The important aspect of DCs is not just imitability or replicability but the ability of organisations to constantly evolve and improve at a pace that is faster than their competitors (Su et al., 2014). Due to rapidly changing environments, SCs will need to constantly adjust their inherent static capabilities and create new DCs that can improve their long-term sustainable performance (Hong et al., 2018).

2.2 | Resilience and its relationship to circular supply chains

Environmental changes are making SCs more complex and vulnerable, making traditional risk management techniques unable to cope with these complexities and turbulences. A proactive response to disruptions requires the building of specific resilience capabilities which can complement traditional risk management approaches of SCs (Nandi et al., 2021; Pettit et al., 2010). Resilience offers capabilities that can help SCs deal with disruptions, make them less vulnerable and help them survive in the long-run (Pettit et al., 2010). Resilience has been defined as 'a measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables' (Holling, 1973, p. 14).

As SCs are increasingly being burdened by excess inventories and associated financial costs, they are being pressured to change their strategies and enhance their capabilities to transform to more sustainable practices such as CE (Bag et al., 2020). Resilience can help SCs realise circular business models and proactively respond to any crisis in dynamically changing environments due to the presence of crucial capabilities (Laumann & Tambo, 2018; Nandi et al., 2021). Supply chain resilience is dependent on capabilities such as flexibility, agility, efficiency, visibility, collaboration and so on (Martin & Peck, 2004; Shin & Park, 2020), which can assist them to respond to market uncertainties, changing customer requirements and disruptive events in a timely manner.

2.3 | Industry 4.0 technologies and principles to promote circular and resilient practices

I4.0 enabled CE practices in manufacturing can give rise to resilient and sustainable SCs (Bag, Pretorius, et al., 2021; Nandi et al., 2021). I4.0 technologies such as Internet of Things (IoT) enable transparency in production with access to information such as resource consumption and underutilized assets, thus contributing to resource-efficient processes and increasing productivity (Ellen MacArthur Foundation, 2016). Quantitatively and qualitatively, the IoT and big data analytics could also substantially improve the capturing of data and monitoring. For instance, the amounts and characteristics of waste in real-time could be monitored and analysed, thereby improving sustainable supply chain performance. Edwin Cheng et al. (2021) concluded that big data analytics capabilities could also address uncertainty by altering flexibility levels and responsiveness of SCs and increase CE practices.

Studies have also identified that artificial intelligence/machine learning and big data analytics can help in extending the life of machines and products through smart maintenance activities, thus reducing the need to replace or remanufacture them before their maximum end-of-life (Chari et al., 2021). The same study saw that an improved availability of data improved the visibility in production logistics and led to shorter lead times, the circularity of materials and improved customer relations. IoT enhanced the flexibility in manufacturing operations by allowing better machine set-ups and seamless adaptation to changing circumstances.

Blockchain capabilities have been known to facilitate CE practices (Esmaeilian et al., 2020) and resilience (Nandi et al., 2021) in SCs by the use of specialised tokens, enhancing the visibility of product lifecycles. By promoting visibility to all actors in the supply chain, blockchain ensures data integrity for materials upstream and downstream. This may help reduce errors, eliminate costs and time delays and enable faster responses (Gaur & Gaiha, 2020; Pournader et al., 2019). Cloud manufacturing also offers opportunities to increase collaboration, knowledge and data sharing further down in the SC, increasing flexibility and resource efficiency (Fisher et al., 2018). Virtual portals offered as services in cloud manufacturing, for instance, SaaS (Software as a Service), IaaS (Infrastructure as a Service) and PaaS (Platform as a Service) allow opportunities to create a shared network of resources and capabilities (Gupta et al., 2019; Yu et al., 2015).

3 | RESEARCH METHODOLOGY

To explore the convergence of DCs, CE and resilience, a multi-method approach based on a qualitative case study design (Yin, 2014) was employed. The research followed an iterative process of data collection and analysis from three independent sources: literature, SCALER project and expert interviews as shown in Figure 1. The need for data from the project was to complement the capabilities identified from the literature, derive key practical challenges to IS implementation and validate the research propositions. Using only literature when designing a study leads to a simplification of the findings. Studies using experts can help make better recommendations (Waltz et al., 2015) and ascertain the content validity of findings (Flynn et al., 1990). Hence, a collaborative exercise using nine domain experts was carried out in this study.

3.1 | Literature review

The scientific database 'Scopus' was used to find relevant publications, with the keywords resilience, circular economy, industrial symbiosis, DCs and capabilities. The terms manufactur*, industr* and supply chain were also added. Articles were then analysed in detail, based on whether they explored specific capabilities that could support the building of resilient and circular manufacturing SCs. During the literature review, several I4.0 articles that described capabilities for sustainability/CE were found. This showed the relative importance of Industry 4.0 technologies and their principles in the development of DCs for CE and these articles were included in the analysis.

3.2 | SCALER project

A study was conducted as part of the SCALER project (SCALing European Resources with industrial symbiosis) (SCALER, 2017) to investigate the potential of IS in Europe. The activities performed here were conducted exclusively for this study.

Between May and July 2018, the study collected data about the triggers, barriers and enablers for effective IS implementation in Europe. The results included best practices, tools and mechanisms to support IS in the European process industry. Data from the study was based on triangulation using the results from an international expert survey, literature and cases demonstrating best practices (Henriques et al., 2019; Vladimirova et al., 2018). The anonymous expert survey consisted of 24 open-ended, multiple-choice questions and was sent to businesses and practitioners across the world who were at different stages of IS implementation. Seventeen respondents representing twelve sectors and eight countries participated in the expert survey. Web of Science was used for a thematic analysis of the title, abstract and keywords of 210 peer-reviewed papers using keywords such as industrial symbiosis, triggers, stakeholders, benefits, decision-making, barriers, tools and technologies. A total of 85 papers were selected as key publications.

In the final step of the study, 25 cases were chosen to demonstrate best practices. The requirements for selecting the cases were that (1) they needed to be published in reputable, publicly accessible sources; (2) the case studies needed to cover a wide range of industries and (3) geographical locations; (4) they had a broad spectrum of IS maturity; and (5) they needed to include self-organized IS systems as well as those created by intermediaries (for example NISP in the UK). The number of case studies enabled a saturation point to be reached, as additional cases provided similar findings (Morse, 1995).

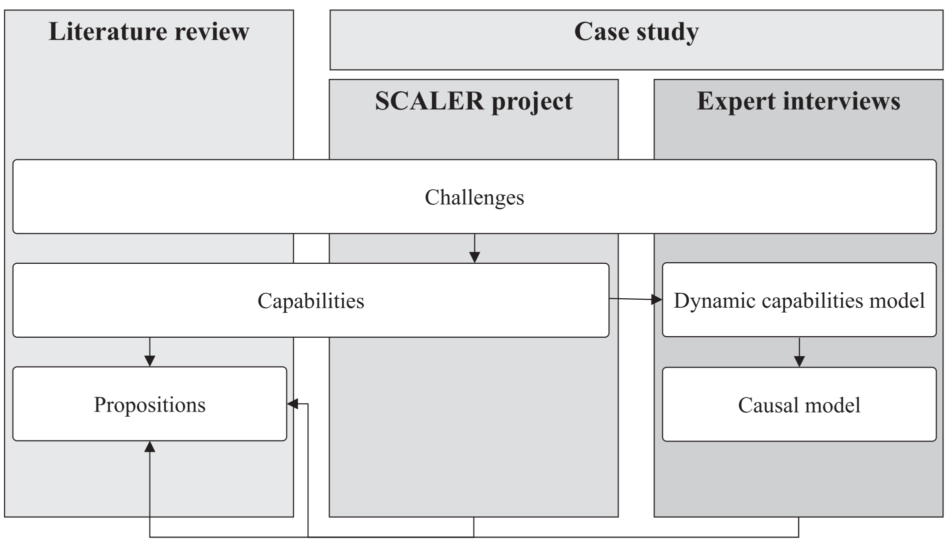

FIGURE 1 The research methodology employed in the paper

3.3 | Expert interviews

Between March and June 2020, nine domain experts were interviewed to complement the theoretical capability findings. The experts (academia and industrial practitioners) were chosen based on a purposive sampling (Lincoln & Guba, 1985) in the fields of I4.0, sustainable supply chain management and CE. Some also had multi-disciplinary expertise in these fields. Details of the chosen experts and their domain knowledge have been described in Table 1.

Data was collected through semi-structured interviews which was guided by a research protocol (Karlsson et al., 2016; Yin, 2014). The capabilities identified from the literature were shared with the experts prior to the interview. Examples of questions asked: 'What capabilities do organisations need to operationalize CE aspects successfully?'; 'If I4.0 is applicable in your field, how have they been/can be beneficial for bringing about CE practices?'. The interviews were informal and lasted around 60 min each. All interviews were recorded with permission from the participants. Each interview resulted in approximately fifteen pages of transcribed data.

The interview data was processed in four stages (Miles & Huberman, 1994). First, audio data was transcribed into raw text during primary processing. In the second and third stage, first and second cycle coding was conducted. In the last step, assertions were formulated. NVivo 12, a qualitative data analysis software (Hutchison et al., 2010), was used to analyse and code the findings from the expert interviews. The interviews helped enrich and find a tentative relatedness of the different capabilities derived from the literature, identify challenges to CE implementation, develop the DC model and validate the research propositions.

A surprising finding during the development of the DC model was that many of the capabilities were found to be related to each other. The Design Structure Matrix (DSM) proposed by Eppinger and Browning (2012) helped showcase the relationships between these derived capabilities. They described the DSM as a network modelling tool that can be used to represent the different elements comprising a system along with their interactions. Causal modelling, as advocated by Blalock (Blalock, 1985; Blalock, 1991) was then used to visualise the interconnections between the capability constructs or 'variables'.

TABLE 1 Description of participants in the expert study

Expert	Domain	Role and expertise
A	SSCM, CE	*Director of research in industrial sustainability* Works with developing structured design and operations solutions to move industries in various sectors towards improving their sustainability performance
B	SSCM, CE	*Project manager, researcher and consultant* Works with resource efficiency in production systems, product design and management for circular economy
C	SSCM, CE	*Project manager* Works with logistics and circular economy projects with a focus on circular business models and closed-loop supply chains
D	SSCM, CE, I4.0	*Associate professor and senior researcher* Works with sustainable logistics and supply chain management
E	IS, CE	*Affiliated postdoc researcher* Works with sustainable production system development within circular material flows
F	IS, CE	*Senior lecturer and action researcher* Works with development determinants and facilitation techniques of industrial and urban symbiosis practices in Sweden and other Nordic and European countries
G	IS, CE	*Assistant professor in sustainability management* Works with corporate environmental management, sustainable consumption and production, environmental footprint, LCA and circular economy
H	I4.0	*Doctoral student* Works with production development and knowledge management, understanding how different interactions between humans and automation can support humans' role in production. The research also focuses on I4.0 maturity models for improving decision support for assembly operations
I	I4.0 and sustainability	*Researcher and consultant* Works with data-driven and model-driven methods and innovation strategies for increasing efficiency of production processes using I4.0 technologies

4 | RESULTS

As seen in Figure 1, four main results are described in this section: Challenges to implement CE, the capabilities derived from the literature and the project, the dynamic capabilities model and the causal relationships model. The research propositions are discussed in section 5.

4.1 | Challenges to implement circular economy

The challenges to implement circular economy in manufacturing SCs identified from the literature, project and expert interviews are described in this section.

Transition to CE practices involves multi-dimensional and multi-domain challenges such as complexity and uncertainty in material flows, development of suitable business models, product design, service and distribution processes and so on (Ritzén & Sandström, 2017). Some other challenges seen in the literature are a lack of collaboration within companies and with SC partners due to misaligned interests, lack of organisational capabilities, cultural mindset and leadership and the inability to take necessary risks (Sousa-Zomer et al., 2018). A summary of critical circular SC barriers in Industry 4.0 was identified and prioritised from a literature review and fuzzy analytical network process by (Ozkan-Ozen et al., 2020). Lack of knowledge and understanding about data management, I4.0 technologies and CE approaches among stakeholders, and a lack of training, organisational willingness, and management support were among the top challenges.

With regards to IS implementation in the project, there was a lack of comprehensive data and information on wastes (due to poor quality, volume and types of data due to varying geographical locations—large distances reduce economic viability, shortages of basic materials; lack of infrastructure, utilities, services and facilities; lack of active community engagement); regulations at firm level (environmental regulations for by-product reuse and water and energy utility regulations; contractual issues; confidentiality issues) and national level (limit the ability of firms to alter their business processes; ingrained market models; lack of specific IS policy; uncertainty on direction of national politics); lack of capabilities was also seen in terms of insufficient human resources and skills shortages; mismatch of capacities/capabilities, leadership support and cultural mindset (lack of motivation, social inertia, mindset from negative experiences); structured methods of incumbents and technology were also seen as barriers—different material recovery technologies and lack of investments in appropriate technologies among the different partners significantly affected the identification of potential candidates for symbiotic resource exchanges.

One of the leading challenges identified from the expert interviews is how the concepts of CE, resilience and I4.0 are understood. Without a clear and standardized conceptualization of CE among organisations, it is difficult to implement CE practices. In addition, there still exists a lack of knowledge in using the appropriate quantitative methods to measure the environmental impact of industries. If organisations are to stay competitive and conform to mounting sustainability regulations and norms, it will be necessary to apply suitable life cycle management methods.

Supply chains also face increasing logistic systems' design challenges in terms of finding the right customer for the new 'refurbished' or 'recycled' product and understanding how the new product will be used. Existing institutional conditions act as constraints and a lack of suitable financing mechanisms inhibits the transition to circular practices. In addition, achieving circularity is not a single-organisation activity and requires support from the SC network, who may not have the same level (or intent) of implementing CE practices.

There could also be difficulties in establishing collaboration between departments within an organisation. For instance, environmental managers may not always cooperate with the R&D department at the beginning of product development or the marketing department for the communication of results. This could lead to sustainability decisions being initiated as stand-alone activities. Hence, there exists a lack of cross-functional horizontal and vertical integration of competencies and communication.

I4.0 has the potential to improve CE efforts as described in Section 2.3. However, it was seen from the interviews that sustainability trade-offs exist in firms when using I4.0 technologies. For instance, although blockchain is being used to monitor material flows and trace products along the SCs, one needs to be aware of the energy source of these technologies. In another example, some automotive industries are developing new materials using I4.0 technologies to build structural components of electric vehicles. Using these new materials could present a sustainability issue even though driving the electric vehicle has a positive environmental impact.

4.2 | Capabilities from the literature review and project

A list of capabilities identified for a manufacturing supply chain are shown in Table 2. A total of 18 categories of capabilities were identified by iteration of data from the literature.

Some of the interesting findings were: data and knowledge about waste and material quality were considered important to design better circular strategies, strategy capabilities in the form of operational, marketing, management and circular were considered critical to promote CE, and flexibility and agility were found to be common resilience practices to achieve circularity. Innovation was seen as a key capability to promote CE as also recognised by Sehnem et al. (2021). They found that innovation was relevant to support the transition to CE practices and build sustainable value chains.

A discussion of these capabilities derived is further elaborated in Section 5.1 and translated into five research propositions. These capabilities were also shared with the experts and analysed to generate the dynamic capabilities model.

4.3 | Dynamic capabilities model

Analysis of the data from the literature, project and expert interviews led to the development of a DC model and a causal relationship model for implementing CE in manufacturing SCs. These models were developed in two stages: (i) iteration was performed between the data collected from the literature (in this study and from the project) which led to the identification of capabilities (Table 2) (ii) the capabilities were then validated by the experts having varying levels of expertise in the chosen domains to give rise to categorisation under DCs (Table 3). This validation provided feasibility in an organisational context as well as helped refine and develop the final model (Platts, 1993).

From the nine interviews conducted, 38 1st-order categories emerged from the in-vivo informant or expert quotes. The similarities

TABLE 2 Capabilities to promote CE (from the literature findings)

Categories	Capabilities identified	Reference
Data	- Manage waste quality - Data management (processing and transformational) capabilities can lead to better insights for circular supply chains	(Awan et al., 2021; Bag & Pretorius, 2020)
Knowledge	- Knowledge about designing new strategies - Knowledge about material composition and social behaviour	(de los Rios & Charnley, 2017; Kabongo & Boiral, 2017; Lewandowski, 2016)
Human	- Workforce skill development - Information processing - Technical - Managerial - Education and participation	(Bag, Gupta, & Kumar, 2021; Bag et al., 2020; Cezarino et al., 2018; Díaz-Chao et al., 2021; Hussain & Jahanzaib, 2018; Kristoffersen et al., 2020; Schuh et al., 2020; Shayganmehr et al., 2021; World Manufacturing Forum, 2019)
Physical	- Tangible resources	(Bag & Pretorius, 2020; Bag, Gupta, & Kumar, 2021; Dangelico et al., 2017; Prieto-Sandoval et al., 2019)
Operational strategy	- New organizational structures - Competitive capabilities - Development of standards	(Bag & Pretorius, 2020; Hussain & Jahanzaib, 2018; Lewandowski, 2016; Souza et al., 2017; Ünal & Shao, 2019)
Marketing strategy	- Develop sound marketing strategies	(Bag & Pretorius, 2020)
Management strategy	- Environmental management - Customer management - Supplier management - Product management - Process management - End-of-Life management	(Díaz-Chao et al., 2021; Hussain & Jahanzaib, 2018; Laumann & Tambo, 2018; Scarpellini et al., 2018)
Circular strategy	- User-centred design - Dematerialization - Creation of CE indicators	(de Sousa Jabbour et al., 2019; Hussain & Jahanzaib, 2018)
Leadership	- Behaviour of leaders - Top management commitment and support	(Bag & Pretorius, 2020; Shayganmehr et al., 2021; Souza et al., 2017)
Culture and mindset	- Shared culture among members - Integrating sustainability into the core of business (strategic mindset) - Openness to recycled products	(Hussain & Jahanzaib, 2018; Machado et al., 2019; Schuh et al., 2020; Souza et al., 2017)
Value capture	- Identification and evaluation of opportunities	(Hussain & Jahanzaib, 2018)
Production	- Product design and development - Production and delivery - Support and maintenance - Security and safety	(Baas, 2008; Hussain & Jahanzaib, 2018; Shayganmehr et al., 2021; Watson et al., 2018)
Resilience	- Flexibility - Agility - Efficiency - Alertness - Change management - Robustness	(Ates & Bititci, 2011; de Sousa Jabbour et al., 2019; Díaz-Chao et al., 2021; Fabbe-Costes & Ziad, 2021; Pettit et al., 2010; Prosman & Wæhrens, 2019; Shayganmehr et al., 2021; Shin & Park, 2020; Ünal & Shao, 2019)
Financial	- Cost efficiency capabilities will be required to ensure success of circular businesses	(Sousa-Zomer et al., 2018)
I4.0	- Technological upgradation - Connectivity - Digital competency	(Bag & Pretorius, 2020; Jakhar et al., 2019; Price Waterhouse Cooper, 2016; Scarpellini et al., 2018; Schuh et al., 2020; Shayganmehr et al., 2021; Souza et al., 2017)

TABLE 2 (Continued)

Categories	Capabilities identified	Reference
Innovation	- Best practices adoption - Knowledge integration - Production Innovation	(Gupta et al., 2019; Kabongo & Boiral, 2017; Khan et al., 2021; Romero et al., 2021; Sehnem et al., 2021; Storer & Hyland, 2009)
Within company	- Collaborative innovation capabilities are crucial to adopt CE strategies	(Bag & Pretorius, 2020)
With external stakeholders	- Interorganisational cooperation with different companies	(de Sousa Jabbour et al., 2019; Edwin Cheng et al., 2021; Hussain & Jahanzaib, 2018; Sousa-Zomer et al., 2018)

and differences in these categories were then carefully studied, to understand the deeper structures and relationships existing within the derived data. This then led to the more abstract 2nd-order thematic level of coding. These codes were further combined into 'aggregate dimensions' or 'microfoundations' of DCs. Underpinning the capability constructs (1st order informant/participant quotes) to several microfoundations of DCs (2nd order abstract or theoretical codes), factors such as communication, resources, organisation, collaboration and technology were bundled as the microfoundations of DCs (aggregate dimensions). These were then categorised into 'sense', 'seize' or 'transform' DCs.

An interesting finding was that the derived capability constructs could not be classified under only one dynamic capability each but were categorised under more than one dynamic capability of sense, seize and transform. Excerpts from the interviews are described in the following sections.

4.3.1 | Sense

Despite CE being increasingly well-defined as a concept and set of strategies, it is not always clear how manufacturing companies can develop or adapt their circular business models. A practical definition of CE principles applicable to manufacturing is urgently required to remedy this lack of clarity. This definition extends to the SC as well: if business models are not aligned across the SC, then circular solutions may not be technically or economically feasible, for example, products are not designed for longevity, repair, disassembly and remanufacturing, or cannot be collected and reprocessed in ways that retain their value. In addition, circular strategies, definitions and practices are not standardized, complicating conceptualization in the sense stage.

In some companies, the reverse may be true: even if CE knowledge exists in a company, it may not necessarily be communicated in a manner that allows waste to be visible and viewed as a potential source of value. For instance, expert B mentioned that some metal companies communicate the weight of waste produced, others express waste as the number of products being disposed of, and others define waste in terms of monetary value. These different metrics and indicators of waste make it difficult to communicate between companies, but also miss the value embedded in waste. A good communication capability needs to be developed from a top-down/bottom-up approach, across functions within the company, as well as across the entire SC. Internal communication between the companies plays a critical role as the foundation for CE transition.

When critical knowledge on a specific material is missing, companies use other alternatives. Due to this lack of knowledge and uncertain consequences of designing a product for CE, companies are unwilling to take the necessary risks and develop the necessary strategical capabilities. Responses to opportunities and risks cannot be an ad hoc problem-solving capability (Teece, 2007) and the most desired approach is embedding the necessary microfoundations within the entire organisation and its SC. If one can 'sense' circularity, then seizing and transforming can become standard DCs. This sensing is both an external and internal exercise. A company can only know if they are achieving circularity (by external sensing) if the concept of CE is well established and matches with what they are internally sensing.

4.3.2 | Seize

While the barrier to CE transition generally lies in the conceptualization phase, IS transition is generally hindered in the implementation phase. That is, the concept of selling waste as an input to another industry is easily conceptualised, but the more challenging step is in the implementation or the 'seizing' capabilities phase. A quantity mismatch of by-products can hinder the seizing of symbiotic opportunities and cannot be overlooked in this phase.

Trust is an important factor, as it is needed to overcome the problems associated with moving by-products or waste, such as variations in quality, cost and time. Trust can be achieved by the development of skills, which can improve collaborations and communication between the different entities of the SC. Accessing reliable information is critical for larger commodity supply chains, where a single source of information (supplier) may be insufficient to guarantee trust (Villena & Gioia, 2018). Specifically, lower-tier suppliers have typically less awareness and knowledge about sustainability-related practices, receive less pressure from public society and are located in countries where social and environmental regulations are not prioritized (Villena & Gioia, 2018). Hence, the importance of building trust,

TABLE 3 The dynamic capabilities model for CE implementation

Dynamic capabilities model			Micro-level capabilities		
Microfoundations of dynamic capabilities *(aggregate dimensions)*	**Categories *(2nd order codes)***	**Interviewee quotes *(1st order codes)***	**Sense**	**Seize**	**Transform**
Communication	Data	- Systematise sharing of data for better production, ergonomics and logistics[e, h] - Source local materials to have data inflow at different stages of manufacturing[d] - Understand data that you have, and the data sharing needs of the different partners in the value chain[h] - Understand the requirements of data derived from technologies & how to present results[h]	x		
	Knowledge	- Gather information at the design phase to make more sustainable products[c] - Identify customer needs for the purpose of the product[c] - Standardize definition of data and circular economy[a, b, c, d, e, f, h] - Strive for common education and knowledge sharing due to similar problems in the value network[e]	x		
Resources	Human	- Educate workers on circular economy practices on the shop floor[c] - Develop the right skills for enabling the right material flows and maintain eco-efficiency[e] - Incorporate attention to human rights, employee well-being and inclusivity[d]		x	
	Physical	Assign resources to operations that are not the core of the business[e]		x	
Organisation	Operational strategy	Build new supply chain structures, logistics systems and logistics structures[d]		x	
	Marketing strategy	Develop environmental-oriented priorities rather than only action-oriented (from I4.0)[g]	x	x	
	Management strategy	Understand allocation of responsibilities between manufacturers, suppliers, and users[c]		x	
	Circular strategy	- Involve local partners for circular economy activities[c] - Develop indicators to measure share of reused/recycled products in the market along with extending its utility value[c]		x	
	Leadership	- Support from top-level management[c] - Internal motivation and commitment towards environmental improvement[g]	x	x	
	Culture and mindset	- Cultivate a different strategic mindset[f] - Willingness to change within different hierarchical levels[b] - Change in mentality of not only the individual companies, but also in the different companies of the collaboration network[d]		x	
	Value capture	- Reconfigure business models that combine physical asset and service as a product[e] - Make visible and create good relationships to recognise business opportunities[f]	x	x	

TABLE 3 (Continued)

Dynamic capabilities model			Micro-level capabilities		
		- Explore new 'inter-organisational' transparent and equitable business models[f]			
	Production	Develop new manufacturing processes, procurement of materials and inbound logistics[d]		x	
	Resilience	Implement agile way of working to accommodate different types and batches of products for CE[c]		x	x
	Financial	- Create suitable financing interests, instruments or structures[f] - Allocate cost of the wastes generated to the right department within the company[b] - Investment in R&D for alternative raw material processing techniques[d]		x	
Technology	I4.0	- Integrate RAMI 4.0 for structured data communication[i] - Use the potential of I4.0 to trace raw materials at its source[d] - Use simulation and maintenance to reduce lead time and increase lifetime of product[i]	x		x
	Innovation	- Innovate at different levels: Business model, process and human interactions[f] - Develop preventive and condition-based maintenance[b]			x
Collaboration	Within company	Support cross functional collaboration within the company[h]			x
	With external stakeholders	- Develop common infrastructural solutions with industry collaboration in the network[e] - Create end-end connection with supplier & waste entrepreneurs for combined decision-making[b]			x

Note: From the interviews: The superscripts on the 1st order codes represent the participants in the expert study as highlighted in Table 1.

collaboration and communication should not be undervalued, as this can help seize new business opportunities.

Over the last few years, it has been seen that organisations are increasingly building their IS infrastructure, and this could bring tremendous opportunities for increased value capture for the organisation. Cultivating a different cultural mindset that goes beyond environmental regulations is the need of the hour, requiring support not only from the top-level management, but the workers who will implement the solutions as well.

4.3.3 | Transform

Supply chains in the EU are increasingly using technology and collaboration within the value network. Several capabilities of I4.0 can be used to implement of CE and IS. For example, smart maintenance and simulation can predict the system's behaviour to reduce errors and material waste (Chari et al., 2021). The experts stated that novel digital manufacturing technologies like 3D printing are being used to develop new materials, optimize productivity and create profits; without considering the quality, content, behaviour and lifetime of these materials.

Despite the potential of I4.0 for CE, decision makers may not recognise it as a viable strategy. Expert F pointed to a lack of understanding and commitment, without which I4.0 will not help change business-as-usual activities. This showcases a strong link between organisational and digital technological capabilities. Some organisations may already have digital infrastructure in place (robots, sensors, IT capabilities) but have yet to develop strategic and organisational capabilities to integrate these and make them more flexible to prevent errors and increase efficiency.

4.4 | Causal relationship model

The relationships identified from the expert interviews between the emergent dynamic capability constructs were structured using Blalock's (1985) causality model as shown in Figure 2. The dependent variables were placed on the right of the diagram and the independent variables on the left. One-way arrows connected the variables along

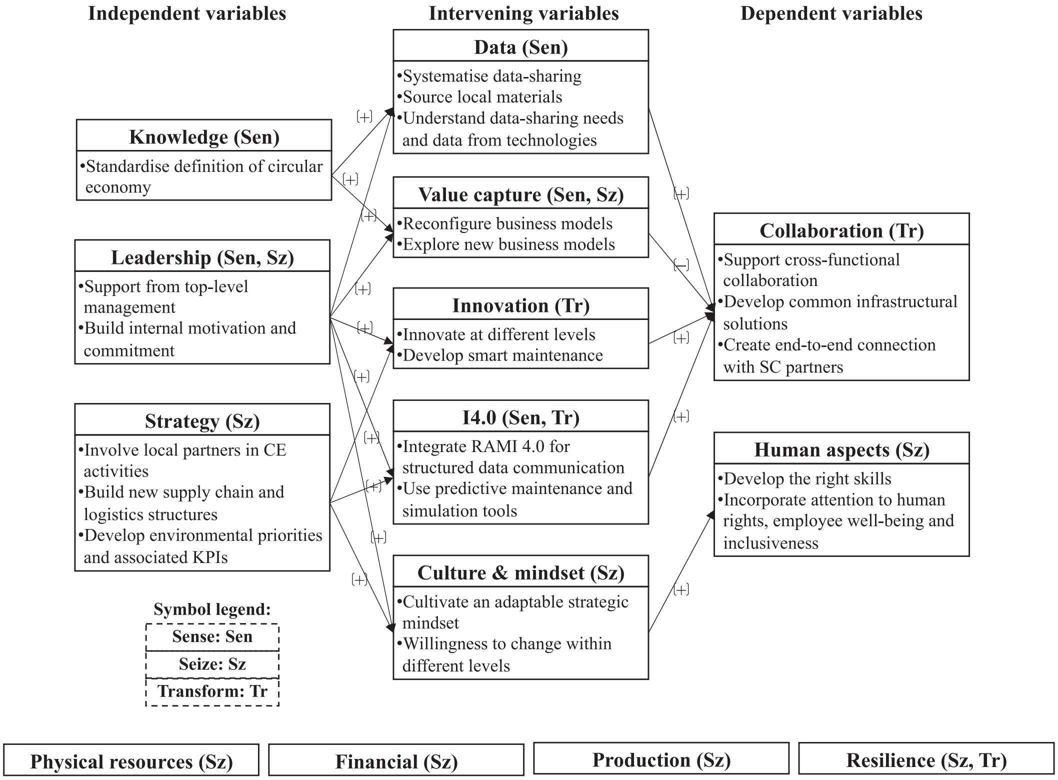

FIGURE 2 Causal model depicting the relationships among the different capability constructs (adapted from Blalock, 1985). The relationships between the capabilities at the bottom of the figure were not explicitly defined)

with positive or negative valences indicating the direction of the relationships. The relationships between the dynamic capabilities at the bottom of the figure could not be explicitly identified from the expert interviews.

The experts identified leadership (support from top-level management) as a significant contributor to other DCs' development. As the definition of CE is still not standardized in firms today and is part of external discussions within SCs, leadership does not affect this construct directly. Similarly, data should be able to be measured and defined consistently for successful cross-functional collaboration among partners. The plurality in CE definitions and interpretations makes it difficult to build new business models and tools (value capture) within the organisation and in other SC partners.

Experts mentioned that company culture can bring employees onboard with the changes in manufacturing processes, by facilitating skills development. The right skills coupled with the company culture affects collaboration and these have together been depicted with positive valences. Companies will constantly need to iterate between measuring (collect data and select indicators) and improving (interpret results) due to constantly changing business environments when manufacturing processes and business models are developed, modified or changed. This is depicted by the relationship between I4.0 capabilities and manufacturing strategy. Value capture is then related to collaboration, as CE efforts cannot take place without the support of other SC partners.

Experts also described that understanding data sharing needs leads to better cross-functional collaboration. Without this understanding, it is difficult to develop a long-term strategy, hence showcasing a dependency between knowledge, data and collaboration. The manufacturing strategy is related to how the company supports collaboration, development and change within the company. The type of company information, data or knowledge will affect the allocation of responsibilities between suppliers and users (causal relationship). Dynamic collaboration in the value network and the type of competencies that exist outside of the focal company are other aspects to consider for successful collaboration within the SC.

5 | DISCUSSION

To complement the literature findings, we identified DCs enabling resilient and CE-related activities in manufacturing SCs. The extent to which these capabilities are developed varies from company to company, based on requirements and existing maturity levels. Supply chains can identify future business opportunities and generate sustainable advantage by prioritising these DCs. As Porter and Linde (1995) described, manufacturing companies trade capabilities against each other to prioritise certain competitive capabilities. However, others suggest that three to five capabilities achieved simultaneously could give rise to long-term improvements and competitive advantage (Ünal & Shao, 2019).

From the literature analysis and corresponding gaps identified, we also developed five research propositions and preliminarily validated them using data from the project and expert interviews.

5.1 | Research propositions

A conceptual framework was formulated drawing on previous work on DCs, CE, I4.0 and resilience for sustainable SCs (Figure 3). The five propositions (Propositions 1–5) mapped in the framework were developed to address the gaps identified in the literature.

This study focused on DCs and their relationship to circular and resilient practices for sustainable SCs. Other relationships should be explored in future work. Although I4.0 was not the main focus in the study, its significance in the literature made it relevant to include in the conceptual framework and propositions. A preliminary investigation revealed that Propositions 1, 2 and 4 could be empirically validated, but Propositions 3 and 5 require further data collection to be developed into hypotheses and tested.

> **Proposition 1.** Dynamic capabilities offer opportunities to generate sustainable competitive advantage in manufacturing SCs.

Buzzao and Rizzi (2020) identified methods to measure DCs for sustainability and improve decision making for sustainability challenges. Capabilities in the form of technological, environmental (Hofmann et al., 2012; Scarpellini et al., 2018), human capital (Díaz-Chao et al., 2021) and strategy (Hussain & Jahanzaib, 2018) can be a source of sustainable competitive advantage in manufacturing. Competitive capabilities such as cost, delivery, quality and flexibility can help firms achieve long-term sustainable competitive goals in SCs (Ünal & Shao, 2019). However, most studies focus on static operational capabilities without exploring the DCs required, leading to Proposition 1.

From the interviews, the 'transforming' technological capabilities seemed to be intervening and dependent variables. To maintain these DCs, strong leadership and a sound sustainability strategy are required. This strategic management is equally important to manage external activities (Teece, 2007) in the SC to increase sustainability performance.

> **Proposition 2.** Dynamic capabilities have a positive role in CE adoption in manufacturing SCs.

Several CE models and frameworks (Kristoffersen et al., 2020; Laumann & Tambo, 2018; Pieroni et al., 2021) were developed to provide proactive guidance to organisations to implement CE practices. Innovative capabilities can promote CE transition through sharing and collaboration (Jakhar et al., 2019; Sun, 2021). Other important capabilities such as participation in collaborative circular networks, knowledge on designing new business strategies and engaging with the different SC partners (Sousa-Zomer et al., 2018) such as waste suppliers can further enhance the waste quality management capability which is an important aspect for IS. Capabilities such as culture (openness to recycled products), user-centred design, dematerialisation and creation of CE indicators were identified for different production and SC levels (de Sousa Jabbour et al., 2019). Customer and supplier management along with product and process management capabilities also enable circular transition (Laumann & Tambo, 2018). Change management is an especially essential organisational capability in SMEs (Ates & Bititci, 2011).

Adoption of Environmental Management Systems (including human resources involved) and level of accountability were identified as important DCs when introducing CE (Scarpellini et al., 2020). Khan et al. (2021) identified key sense, seize and transform DCs to implement CE practices. Although 'dynamic' capabilities can positively aid

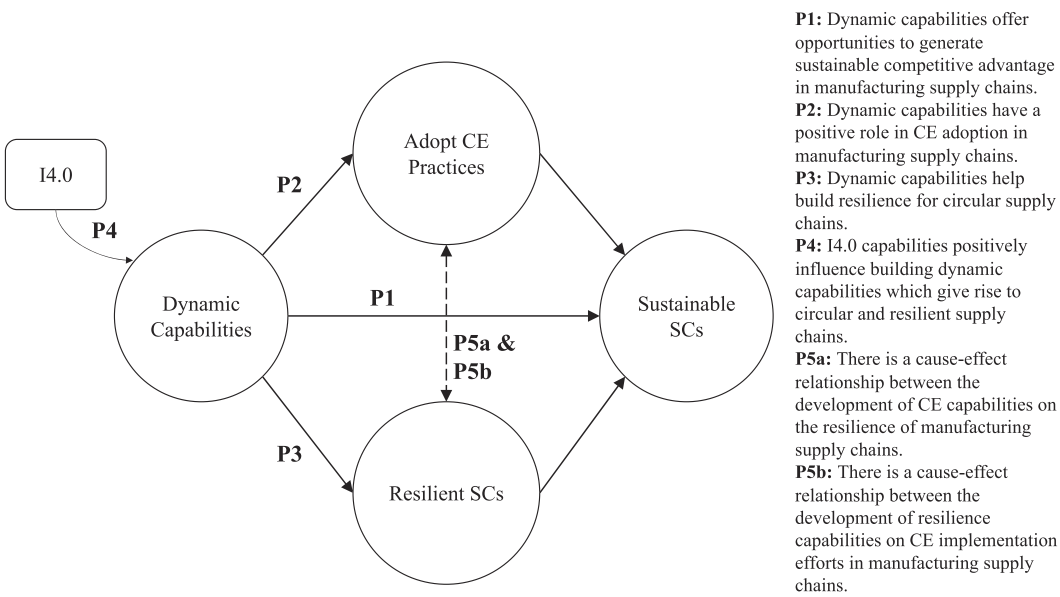

FIGURE 3 Conceptual framework

in adopting CE practices (Khan et al., 2020, 2021; Scarpellini et al., 2020), they are largely unexplored, leading to Proposition 2.

Supply chain management literature focused on operational level capabilities but overlooked those related to human resources (Polyviou et al., 2019). The present study found that DCs associated with the human aspect were important to build circular and resilient SCs. To transition to CE, negotiating and collaborating to develop the skills of SC partners (horizontal integration), and across functions (vertical integration) should remain a priority (Eamonn, 2015). The empirical data also show that DCs such as a mindset change (open-mindedness and freedom to act) and specialised expertise for IS, can enable resource synergies between companies.

Proposition 3. Dynamic capabilities help build resilience for circular SCs.

Resilience conceptualisation requires a continuous adjustment and implementation of capabilities (Conz & Magnani, 2020). Specifically, manufacturing organisations should be able to scan and mitigate potential threats through production innovation capabilities to stay competitive in unstable environments (Romero et al., 2021). Dynamic capabilities in the form of production flexibility (Díaz-Chao et al., 2021) and remanufacturing (Bag et al., 2019) also provide opportunities to build resilience. Souza et al. (Souza et al., 2017) found that DCs can build resilience for sustainability, and conversely, resilience is an eco-capability supporting organisational, human and technological capabilities. Su et al. (2014) stated that resilience is a 'dynamic' capability that organisations could adopt to meet with environmental demands. Although robustness was found to be a key factor to build industrial resilience for sustainability (Chari et al., 2021), robustness and resilience were different concepts in an automotive SC (Fabbe-Costes & Ziad, 2021). This led to Proposition 3 to explore resilience further.

The interviewees suggested that resilience capabilities, such as agile practices, help manufacture different types of products for CE. Proactive resilience capabilities help dealing with disruptions and accommodate CE practices compared to reactive and defensive approaches as also supported from the literature (Ates & Bititci, 2011; Laumann & Tambo, 2018; Nandi et al., 2021).

Proposition 4. I4.0 capabilities positively influence building dynamic capabilities which give rise to circular and resilient SCs.

Developing core capabilities in the form of data and analytics can improve business processes (Price Waterhouse Cooper, 2016). Specifically, business data analytics capabilities in the form of organisational resources can help optimise resource efficiency and productivity (Kristoffersen et al., 2020). Advanced manufacturing capabilities provided by I4.0 can transform traditional linear operations into circular ones (Atif et al., 2021; Bag, Pretorius, et al., 2021; Edwin Cheng et al., 2021) and build resilience (Bag & Pretorius, 2020; Chari et al., 2021). Infrastructure capabilities can help gather data from different sources in the SC and create useful information for strategy formulation and decision-making (Bag et al., 2020). Workforce skills and knowledge such as programming, big data analytics and artificial intelligence are important tacit capabilities (Bag, Gupta, & Kumar, 2021). I4.0 can support procurement for resource flexibility (adaptive capability), integrate internal and external integration (absorptive capability) and innovation (innovative capability) to gain competitive advantage (Bag et al., 2020). Conversely, greater the organisational flexibility, higher the I4.0 technology adoption (Bag, Gupta, & Kumar, 2021).

Several digital maturity models (da Silva et al., 2019; Machado et al., 2019; Schuh et al., 2020; Schumacher et al., 2016) and sustainable operations management literature (Machado et al., 2017) have described capabilities required to keep up with the fourth industrial revolution. They consider the technological and organisational aspects while defining the capability dimensions, leading to Proposition 4 about implementing I4.0 to build relevant DCs.

I4.0-enabled CE practices in manufacturing can support resilient and sustainable SCs (Bag, Pretorius, et al., 2021; Nandi et al., 2021), with a potential to reach tiers further down in the SC. The interviewees suggested that SCs could seize opportunities from I4.0 to improve their DCs (Hong et al., 2018), build context-specific capabilities adding to their overall business value (Hussain & Jahanzaib, 2018) and control and monitor suppliers in the SC. The empirical data pointed to trust, data and transparency issues; thus, leadership and strategy capabilities are needed for I4.0 to support collaboration capabilities which play a significant role for CE transition.

Proposition 5a. There is a cause-effect relationship between the development of CE capabilities on the resilience of manufacturing SCs.

Proposition 5b. There is a cause-effect relationship between the development of resilience capabilities on CE implementation efforts in manufacturing SCs.

As described before, CE opportunities need to be considered for resilient production and consumption patterns (Laumann & Tambo, 2018). However, CE capabilities may require redundant resources, thus negatively influencing CE. In addition, the development of localisation, agility and digitalisation characteristics can enable resilient and circular SCs (Nandi et al., 2021). Supply chains should find a trade-off between these concepts based on their manufacturing strategy. This two-way relationship between CE and resilience remains largely explored, leading to the above two propositions linking the two concepts. These propositions need further empirical investigation in future work.

5.2 | Research quality

The validity of the developed DC model was checked using multiple procedures to confirm the accuracy of the findings (Creswell, 2003): (i) triangulating different sources of data (literature, expert interviews and case study) to check external validity (Yin, 2014) and ensured that the results are relevant for researchers and practitioners. The emergent themes and microfoundations were possible only because of this data convergence, hence adding validity to the study; (ii) the capabilities were shared at the initial development stage with the experts, allowing them an opportunity to comment on the findings.

To check for reliability of the research approach, the following procedures as suggested by Gibbs (Gibbs, 2007) were applied: (i) interviews were transcribed using the AI software Otter.ai (Otter Voice Notes, 2020) and the transcribed notes were rechecked with the audio to ensure obvious mistakes had not occurred during the transcription process; (ii) a qualitative codebook in the form of an excel document was maintained, with the data continually checked against the codes to make sure that the meaning of the codes had not shifted during the coding process; (iii) the analysis was shared and documented on a regular basis among the co-authors, to ensure that the findings were consistent and stable.

6 | CONCLUSIONS

This research explored how DC theory could promote circular and resilient SCs, from theory and empirical evidence. Each of these aspects have mainly been considered as stand-alone topics, but their convergence has not yet been explored, especially from a SC perspective. The first step was to collect data from the literature, a European project and expert interviews. This helped to understand the organisational challenges in their efforts towards CE implementation. The next step was to find possible solutions to overcome these barriers, leading to three central findings of this study: the proposed DC model to transition to CE (Section 4.3), the causal relationships between the capabilities (Section 4.4) and a validation of the propositions using empirical data for circular and resilient SCs (Section 5.1).

6.1 | Research implications

The study makes a novel theoretical contribution to better understand the relationship between CE, resilience and I4.0 using DC theory. The theoretical approach of using DCs to support circular and resilient manufacturing SCs has rarely been adopted. In addition, the new insights gained from this study makes inferences to a research area at the convergence of these topics. Although industry experts highly recommend a shift to CE, the knowledge of how to reconfigure business models is lacking. Joint research between industry and academia is required to support organisations and identify the business opportunities of approaching CE from a dynamic capability perspective.

6.2 | Practical implications

Although SCs are slowly progressing towards circular implementation efforts, organisations still do not know how to implement these efforts in a well-structured holistic manner. In addition, the relationship and links between the different capabilities show that it may be difficult for SCs to develop DCs in isolation. A recommendation to businesses and their SCs is to identify and map the DCs which could support their CE transition and enhance their resilience.

The models depicted in Table 3 and Figure 2 may be valuable tools to understand the multidimensionality of DCs and enabling microfoundations, leading to successful business strategies and outcomes. Microfoundations are unique to specific organisations and their SCs, that help them attain sustainable competitive advantage (Teece, 2007). Apart from basic operational performance competence, companies that can implement the microfoundations may outperform the sustainability credentials of their competitors. The preliminary validation of the propositions also provided empirical evidence of the relationships between the capabilities derived from the literature.

6.3 | Limitations and future research direction

The present research used qualitative data from nine experts and an industrial project (which used 17 survey respondents and 25 cases with best practices that were chosen with specific criteria and data saturation considerations). The experts were selected from the areas of CE, IS, I4.0 and sustainable supply chain management. Due to the novel convergence of these topics, the themes that emerged from the interviews were saturated requiring no further data collection (Charmaz, 2006). In addition, the objective of the DC model was to highlight the relationships among the critical DCs (rather than provide a comprehensive list of capabilities) to remain competitive and promote circular, resilient SCs.

Capabilities to build resilient and circular SCs can be prioritised using multi-criteria decision methods such as fuzzy ANP (Ozkan-Ozen et al., 2020) or other modelling methods such as structural equation modelling (Khan et al., 2021). Additional quantitative approaches could further characterise the DC model/causal relationship constructs with business practices (Edwards & Bagozzi, 2000). Industry-specific studies could provide a deeper understanding of the intricacies that lie within specific sectors. Longitudinal studies could reveal how the capabilities, resilience and CE/I4.0 practices change over time.

In future work, we plan to conduct Delphi studies to further deepen and consolidate the findings. The five research propositions will also be empirically investigated in a manufacturing SC context.

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CONFLICT OF INTERESTS

None.

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