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Assessing smart circular supply chain readiness and maturity level of small and medium-sized enterprises

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ABSTRACT

A Smart Circular Supply Chain (SCSC) integrates both Industry 4.0 (I4.0) and Circular Economy (CE) concepts into supply chain in response to achieving sustainable goals/agenda. The purpose of this paper is to assess SCSC readiness and maturity level of SMEs considering different stakeholders from a multi-layered perspective. For this aim, a conceptual framework was proposed and accomplished through a case study of SMEs in Turkey's textile industry. Such integrated approach to holistically assessing SCSC readiness and maturity makes a unique contribution to the field. The highlights of this study are summarized as follows: (1) approaching readiness and maturity in transitions by focusing on systems theory; (2) identifying the dimensions of readiness and maturity in transitions to I4.0 and CE; (3) assessment of readiness and maturity level of SMEs in transition to CE and (4) assessment of readiness and maturity level of SMEs in transition to I4.0 within the supply chain.

1. Introduction

According to the United Nations, the global population has grown from 3 billion in 1960 to 7.7 billion in 2019 and it is expected to reach 8.5 billion in 2030 (Balestrucci, 2020; United Nations, 2019). Such rapid and substantial growth has significantly raised the demand for natural resources, which is increasing the pressure on natural ecosystems and can potentially lead to catastrophic environmental consequences (Balestrucci, 2020; Nykvist et al., 2009). One of the major organizational responses to this global challenge is the Circular Economy (CE). Unlike the linear economy, CE avoids generating waste and improves the reuse of resources by utilizing the cradle-to-cradle design (Kayikci et al., 2022b). More broadly, CE is an economic model aiming at the effective use of natural resources for waste minimisation, expansion of product life cycles, removal of primary resources, and closed-loops of goods, components of products, and materials in the context of environmental sustainability and socio-economic advantages (Morseletto, 2020). Such aims of CE can be obtained by various business models (Sehnem et al., 2022), such as shared consumption models, products-as-services, CE regenerative principles (repair, refurbishment, remanufacturing, replacement, regeneration, recovery, etc.), and industrial symbiosis. Thus, the concept of the CE is often addressed as the solution to multiple sustainability challenges, such as the generation of waste and resource scarcity, and also brings sustained economic benefits (Ormazabal et al., 2016; Lieder & Rashid 2016). The utilisation of product/service is maximised by consumers or other companies, and the waste is redirected and returned to the economy via closed-loop industrial processes (Kayikci et al., 2021a; Ormazabal et al., 2016).

However, the discussion on the CE is primarily focused on environmental practices and gains: more attention is required to decide how the CE model can deliver benefits and how it can be applied at the company for the ecosystem level (Parida et al., 2019; Frishammar & Parida, 2018; Su et al., 2013). Both reverse (closed-loop) and forward (open-loop) flows of goods, materials, as well as other resources such as by-products and waste, can be integrated into circular supply chain processes (Batista et al., 2018). In particular, by addressing reverse and forward flows, the closed-loop model provides a valuable baseline for describing the potential for applying a circular supply chain design.

Along with the CE, Industry 4.0 (I4.0) has also gained importance in

Abbreviations: SCSC, Smart Circular Supply Chain; CE, Circular Economy; I4.0, Industry 4.0; IoT, Internet of Things; SMEs, Small and Medium-Sized Enterprises; SDGs, Sustainable Development Goals.

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Nomenclature

$c_{kij}^{readiness}$	circularity sub − dimension j score of dimension i of company k for readiness
$s_{kij}^{readiness}$	smartness sub − dimension j score of dimension i of company k for readiness
$c_{kij}^{maturity}$	circularity sub − dimension j score of dimension i of company k for maturity
$s_{kij}^{maturity}$	smartness sub − dimension j score of dimension i of company k for maturity
$\vartheta_{readiness}^{c}$	circularity readiness index score
$\vartheta_{readiness}^{s}$	smartness readiness index score
$\vartheta_{maturity}^{c}$	circularity maturity index score
$\vartheta_{maturity}^{s}$	smartness maturity index score
$\vartheta_{readiness}$	readiness index score of SCSC
$\vartheta_{maturity}$	maturity index score of SCSC
ϑ_{scsc}	readiness and maturity index score of SCSC
j	sub − dimension; $j = 1, 2, \cdots n$
i	dimension; $i = 1, 2, \cdots m$
k	company; $k = 1, 2, \cdots r$
n_i	total sub-dimension number of dimension i
r	total number of companies

recent times as a means to provide sustainable outputs and reduce human–machine interaction for easier adoption of sustainability practices (Yadav et al., 2020b). A distinctive feature of the I4.0 is the ability to combine the digital and the physical world, affecting a broad spectrum of industrial disciplines (Rauch et al., 2020; Lee et al., 2015). Many studies have investigated I4.0, its impact, its significance for the sustainable competitiveness of companies, the related technologies, as well as methods, and strategies for its introduction and implementation in industrial enterprises (Rauch et al., 2020; Yadav et al., 2020b). I4.0 technologies can introduce the "smart concept", having an enormous potential to facilitate CE principles. However, despite this potential, there is little awareness and knowledge about how to exploit emerging digital technologies and resources, such as the Internet of Things (IoT), Big Data Analysis, etc. to facilitate the transition to a CE (Pagoropoulos et al., 2017). Supply chains can also be influenced by the application of both CE practices and I4.0 technologies. The supply chain is becoming more costly, complicated, uncertain, and vulnerable, while managers continue to seek cheaper, faster, and better supply chains (Wu et al., 2016). To overcome these challenges, supply chains need to be smarter (Wu et al., 2016; Butner, 2010) and more circular. I4.0 technologies can be fundamental enablers of CE by supporting the management of the flow of goods, such as allowing automatic position tracking and analysis of natural resources with the IoT, optimising waste-to-resource alignment in industrial symbioses networks by real-time collection by Big Data for enhanced resource management (Kristoffersen et al., 2020). For this purpose, Smart Circular Supply Chain (SCSC) is designed to be flexible and versatile, responsive to supply chain challenges and disruptions (Gupta et al., 2019; Butner, 2010).

Some scholars imply that supply chains need to adapt to the new industrial revolution, also known as I4.0 and CE to stay competitive, to respond proactively, and to achieve more sustainable resource management capabilities to bring environmental, social, and economic advantages (Kayikci et al., 2022b; Kayikci et al., 2022c; Kayikci et al., 2022a; Ozkan-Ozen et al., 2020). Furthermore, the implementation of I4.0 and CE in the supply chain may also create an opportunity to achieve Sustainable Development Goals (SDGs) (Kayikci et al., 2021b; Kayikci et al., 2014). However, Small and Medium-Sized Enterprises (SMEs) face great difficulty in reaching a stage of environmental excellence due to their limited resources to adopt the I4.0 technologies and CE practices (Ormazabal et al., 2016; Shi et al., 2008). Ineffective enforcement of relevant regulations, poor institutional support, lack of economic incentives, poor technical skills and low environmental awareness also affects the CE readiness in small firms (Singh et al., 2018; Möllemann, 2016; Rizos et al., 2015; Agnello et al., 2015). However, SMEs are vitally important to economies. Ormazabal et al. (2016) stated that 95% of companies in the Organization for Economic Co-operation and Development (OECD) countries are SMEs, which generate two-thirds of all employment. Specifically, in the European Union, SMEs represent 99% of all enterprises (Filipe et al., 2016). The OECD considers that SMEs are "central to the efforts to achieve environmental sustainability and more inclusive growth" (OECD, 2017).

Yet, the CE is still far from being implemented in industrial companies generally and in SMEs specifically (Ormazabal et al., 2016). SMEs account for approximately 64% of industrial emissions in Europe (Pirola et al., 2020; Calogirou et al., 2010). Many authors recognize that it is highly challenging to achieve the complete implementation of CE principles by organizations and related supply chains due to the absence of modern technologies (Piscitelli et al., 2020; Cayzer et al., 2017; Elia et al., 2017; Bocken et al., 2016). Therefore, organizations need to improve their strategic development plans by including strategic goals and directions for a more consistent adoption of I4.0 technologies (Pirola et al., 2020). I4.0 facilitates the communication of public policies and the recognition by the industry itself, namely, the less sophisticated SMEs, of looming changes with potential implications on their competitive landscape (Castelo-Branco et al., 2019; Smit et al., 2016: Kayikci et al., 2021b). Also, SMEs are usually less informed about I4.0 concepts (Rauch et al., 2020). Since SMEs lack the manpower to look ahead and beyond their product range to enter new areas, as well as usually cannot invest in emerging technologies as an early adaptor, they risk losing money by focusing on potentially the wrong technologies (Faller & Feldmüller, 2015).

This study holistically addresses the issues above by considering the circularity and smartness landscape of supply chains through the smart circular supply chain archetype shown in Fig. 1. CE contributes to the supply chain with the closed and open loops as shown in Blue and Green in the figure. There is a need for SMEs to understand the state of readiness and maturity levels of both I4.0 and CE directions in the supply chain and enable them to prepare and invest in circular principles with I4.0 technologies, which enable the achievement of smarter and more circular supply chains. In the existing literature, the business models studied measure either the level of readiness and/or maturity for I4.0, or CE. Therefore, the development of the readiness and maturity model for both I4.0 and CE is the research gap this study addresses.

Based on the above-mentioned research gap, the objective and contribution of this study is to develop a conceptual model to evaluate both readiness and maturity levels of SMEs concerning transitions to I4.0 and CE practices, including analysis of supply chain ecosystem participants from a multi-tier perspective. In practice, clear levels of maturity allow SMEs to evaluate their stage of SCSC implementation, and strategically plan their development. A maturity model is a measure that enables an organization to classify its maturity into a process ranging from non-existent (level 0) to optimised (level 5) (Grant & Pennypacker, 2006). Maturity models are often used as a tool to conceptualize and measure the maturity of an organization or a process based on a predefined target situation, and the purpose of a readiness model is to set a starting point and initiate the development process. While maturity assessment measures the actual situation during the maturation process, readiness assessment takes place before the maturation process begins (Schumacher et al., 2016).

In order to reach the objective of this study, three research questions arise as follows:

(i). What are the dimensions of readiness and maturity in transitions to I4.0 and CE?

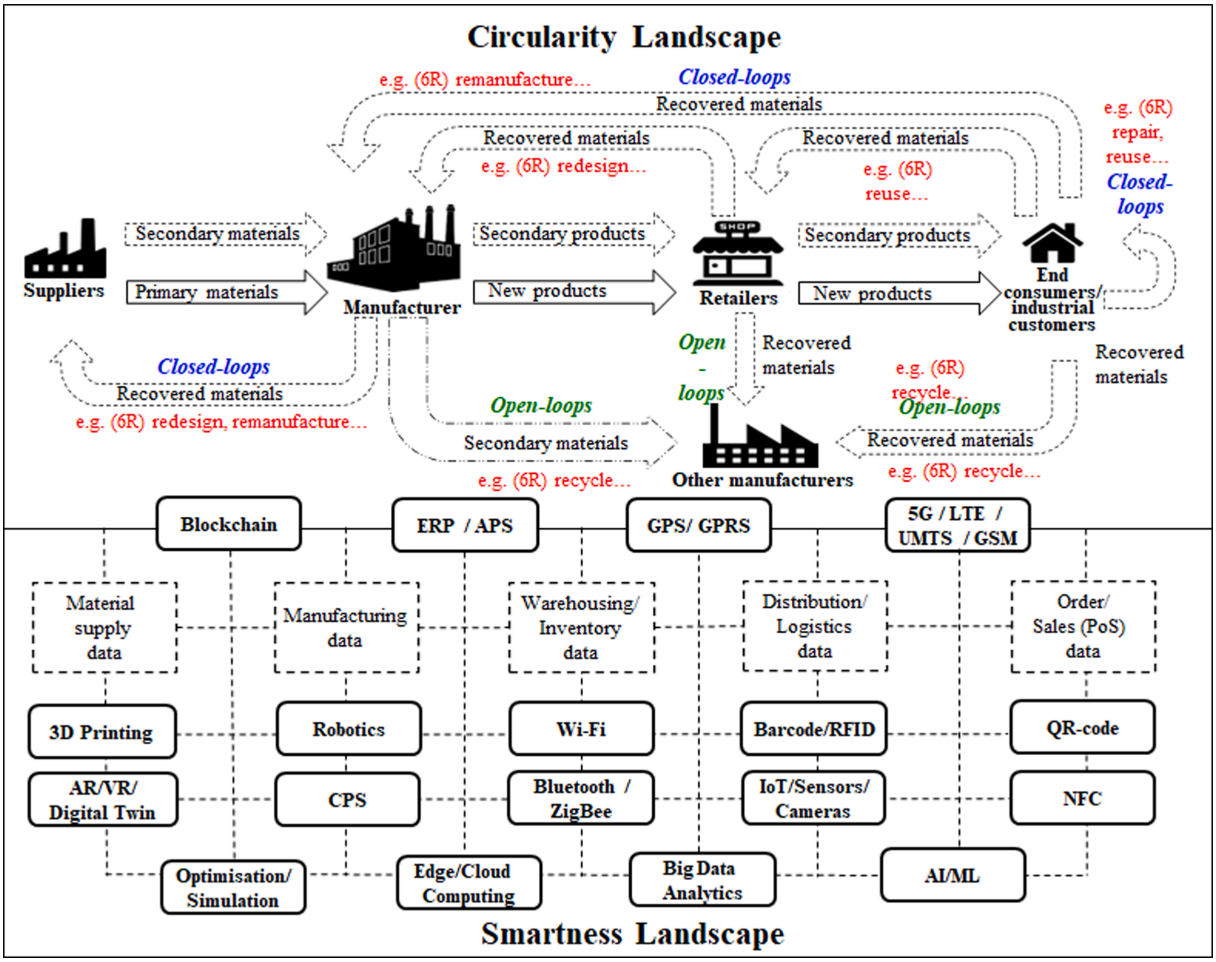

Fig. 1. A Smart Circular Supply Chain Archetype, adapted from Batista et al. (2018, 2019).

(ii). How can the readiness and maturity level of SMEs in transition to I4.0 within the supply chain be assessed? (Smartness landscape)

(iii). How can the readiness and maturity level of SMEs in transition to CE within the supply chain be assessed? (Circularity landscape)

Previous studies emphasized that the simultaneous transitions to I4.0 and CE cannot be achieved within the context of a single company, because these transitions need to be implemented throughout the entire supply chain (Kayikci, 2018). Therefore, the theoretical background of this study is based on the system theory as the theorical lens to consider whole supply chain perspectives. For this purpose, the development of the proposed framework for the assessment of readiness and maturity levels of SMEs regarding I4.0 and CE systems in the supply chain involves multi-dimensions that embrace the whole supply chain.

The paper is organized as follows: Section 2 presents the literature review process and selection of relevant publications and identifies the dimensions and sub-dimensions from the available I4.0 and CE readiness and/or maturity models. Section 3 develops the conceptual framework for the assessment of SCSC readiness and maturity level of SMEs. The developed framework is implemented in Section 4 in a case study conducted with different stakeholders from a multi-layered perspective in the Turkish textile industry. Section 5 presents the result of the study with radar charts and Section 6 discusses the findings. Section 7 gives useful insights into the theoretical, practical and managerial implications related to the study. Finally, the paper concludes with Section 8, which presents conclusions, highlights limitations, and proposes new directions for future research.

2. Literature review

Existing I4.0 and CE studies in the literature have been systematically reviewed to elaborate on the concept of the SCSC readiness and maturity model as demonstrated in Fig. 2. For this purpose, a structured search string was used to search literature databases and find relevant articles for this research. The search strings were presented in Table 1.

The academic databases, publishers' databases, research engines, and open archives selected as sources for the literature review were: ACM Digital Library, IEEE Xplore, Wiley, Science Direct, Springer, Emerald insight, MDPI, Web of Science, Google Scholar, Mendeley, Scopus, and Research Gate. These sources allowed coverage of a wide range of literature addressing readiness and maturity model assessments that take into account CE or I4.0 perspectives and frameworks.

Initially, a total of 317 publications were found and after systematic screenings, 104 were considered suitable for this study. According to the results of current literature reviews, no readiness or maturity model uses both I4.0 and CE. Up to date, only a few studies mentioned the importance of maturity levels for both I4.0 and CE, but none proposes any concept integrating readiness and maturity model for both I4.0 and CE directions. The findings of the reviewed studies are briefly discussed in the subsections below. Summaries of the main dimensions and sub-dimensions of readiness and maturity models considered by the reviewed studies are presented in Table 2 (CE direction) and Table 3 (I4.0 direction). The level type for both tables indicates that R is readiness level and M is maturity level.

A variety of I4.0 technology applications to enable the implementation of the SCSC archetype (Fig. 1) has been identified in the

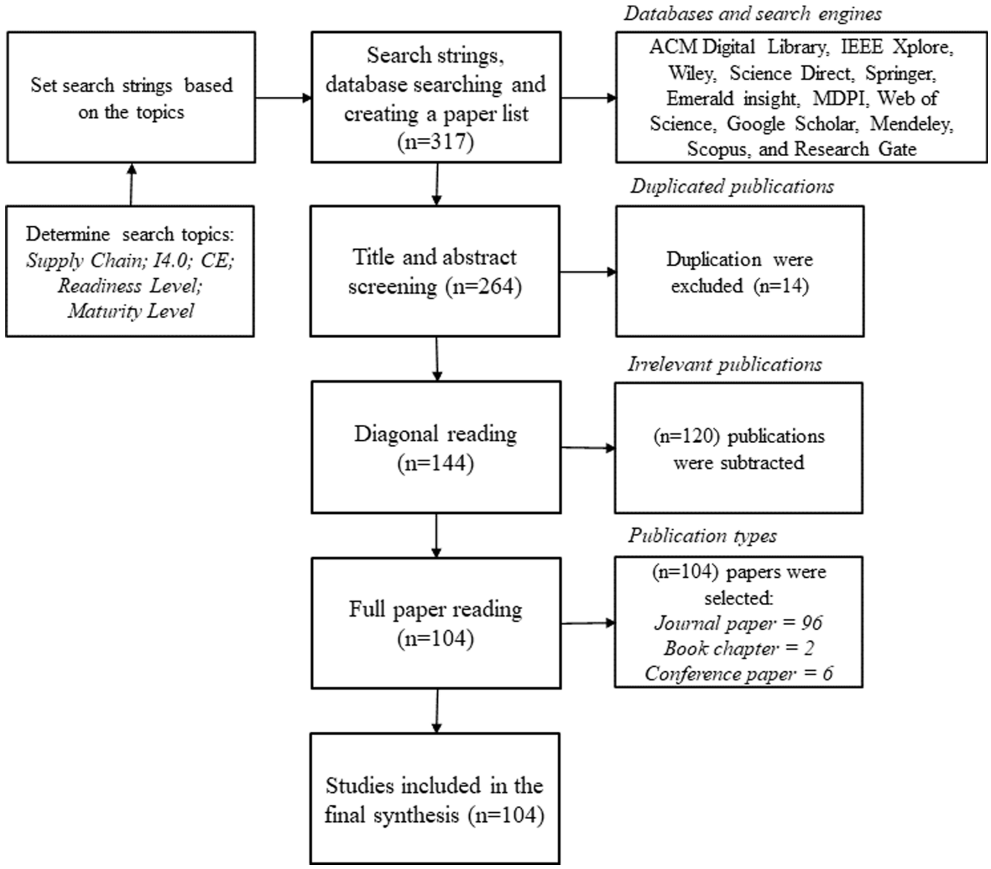

Fig. 2. The Literature Review Flowchart.

Table 1
The Search Strings.

Search topics	Search strings
Supply Chain	{("supply chain" OR "green supply chain" OR "sustainable supply chain" OR "green manufacturing" OR "sustainable manufacturing") AND
Smartness landscape	("Industry 4.0" OR "I4.0" OR "smartness" OR "digit*" OR "3D printing" OR "3DP" OR "augmented reality" OR "AR" OR "virtual reality" OR "VR" OR "digital twin" OR "simulation" OR "robotics" OR "cyber-physical systems" OR "CPS" OR "Wi-Fi" OR "Bluetooth" OR "Zigbee" OR "Barcode" OR "RFID" OR "Internet of Things" OR "IoT" OR "sensor" OR "near field communication" OR "NFC" OR "QR*" OR "cognitive computing" OR "cloud computing" OR "edge computing" OR "Big Data" OR "BDA" OR "artificial intelligence" OR "AI" OR "machine learning" OR "ML" OR "blockchain" OR "ERP" OR "APS" OR "GPS" OR "GPRS" OR "5G" OR "LTE" OR "UMTS" OR "GSM") AND
Circularity landscape	("circular economy" OR "green economy" OR "circularity" OR "circular practices" OR "circular principles") AND
Readiness level/ Maturity level	("readiness" OR "maturity")}

literature, as described in Table 4.

2.1. Readiness and maturity models for circular economy

Zhu et al. (2022) studied CE methods and developed a transformative conceptual model for SMEs from emerging countries. Fletcher et al. (2021) presented a framework for assessing circularity and technological maturity for medical plastic waste management. Martinsen et al. (2021) introduced a maturity assessment model from CE perspectives. Sacco et al. (2021) demonstrated a new tool for the assessment of maturity and circularity. Rizos et al. (2015) identified significant challenges and enablers to implementing CE business practices by evaluating SME circular business model examples. Min et al. (2021) emphasized the need to identify the internal and external hurdles to CE adoption in Chinese SMEs. Mura et al. (2020) examined what measures SMEs need to address in terms of problems and opportunities of CE, by examining actions, barriers, enablers, and the relationship between CE, business strategy, and performance. In this context, twenty different CE practices were investigated, including waste management, packaging, supply chain, and product/process design perspectives. Ünal et al. (2019) investigated SMEs' managerial practices needed to construct a CE business model, and how companies might create and extract value from the CE business model. In order to show a holistic strategy toward value creation and capture in CE business models in SMEs, they studied an Italian company in the office supply sector. Ormazabal et al. (2016) examined the maturity of environmental management, and also the extent to which CE is applied to Basque SMEs. Zamfir et al. (2017) studied corporate decision-making frameworks for the implementation of CE principles, based on European SMEs. Their study provides a clear view of the relationship between the dynamics of European SMEs and CE principles. Singh et al. (2018) explained a Theory of Planned Behaviour model to examine Micro, Small, and Medium Enterprises' readiness for CE. Batista et al. (2018) created an archetype to merge the concepts of CE and supply chain into a circular supply chain model by utilizing four antecedent sustainable supply chain narratives: reverse logistics, green supply chains, sustainable supply chain management, and closed-loop supply chains.

Cristoni & Tonelli (2018) focused on CE maturity and classified the business areas most suited for the implementation of CE, leading to a proposed framework for circularity in business strategy. The primary outcomes indicate low knowledge of the CE potential across industries, and even lower levels of maturity, particularly by SMEs. Niero & Rivera

Table 2
Summary of dimensions and sub-dimensions of existing CE Readiness and Maturity models.

DIMENSIONS	SUB-DIMENSIONS	LEVEL TYPE	REFERENCES
Economic	Business Agility	M	Fletcher et al. (2021); Sacco et al. (2021); Sari et al. (2021); Prieto-Sandoval et al. (2019); Sehnem et al. (2019); Ormazabal et al. (2018); Singh et al. (2018); Zamfir et al. (2017)
	Economic Benefit	M	
	Green Economic Incentives	R	
	Return On Investment	R & M	
Environmental	CO_2 Emissions	M	Liu et al. (2022); Fletcher et al. (2021); Martinsen et al., (2021); Sacco et al. (2021); Balestrucci (2020); Sari et al. (2021); Ferreira et al. (2019); Prieto-Sandoval et al. (2019); Sehnem et al. (2019); Braccini & Margherita (2018); Cristoni & Tonelli (2018); Singh et al. (2018); Zamfir et al. (2017); Romero & Molina (2014)
	Deposition Efficiency	M	
	Eco Industrial Parks	R	
	Eco-Efficiency	M	
	Energy Awareness	M	
	Energy Consumption	M	
	Environmental commitment	R	
	Green Labeling	M	
	Industrial Waste-Water Recycling	M	
	Inefficiency Of Water Usage	M	
	Reuse And Industrial Symbiosis	R & M	
	Sustainability Design For Environment	M	
	Up-Front Network Design	R	
	Waste	M	
	Water Reuse	M	
Social	Ecosystem Participants	R	Fletcher et al. (2021); Sacco et al. (2021); Balestrucci (2020); Sari et al. (2021); Garcia & Cayzer (2019); Parida et al. (2019); Prieto-Sandoval et al. (2019); Sehnem et al. (2019); Braccini & Margherita (2018); Niero & Rivera (2018); Ormazabal et al. (2018); Singh et al. (2018); Verstraeten-Jochemsen et al. (2018); Despeisse et al. (2017); Zamfir et al. (2017)
	Employee	M	
	Ethical Behaviour	M	
	Individual Behaviour	R	
	Labor Practices	M	
	Social Pressure	R	
	Society/ Customers	R & M	
	Work Culture	R & M	
Policy	Corporate Sustainability Policy	R & M	Liu et al. (2022); Fletcher et al. (2021); Sacco et al. (2021); Balestrucci (2020); Barletta et al. (2020); Sari et al. (2021); Garcia & Cayzer (2019); Parida et al. (2019); Sehnem et al. (2019); Zamfir et al. (2017)
	Employees	M	
	Governance	M	
	Incentives	M	
	Organizational Culture	M	
	Regulations	R & M	
Process	End-Of-Life Cycle	R & M	Huang et al. (2022); Fletcher et al. (2021); Martinsen et al., (2021); Balestrucci (2020); Barletta et al. (2020); Sehnem et al. (2020); Garcia & Cayzer (2019); Sehnem et al. (2019); Braccini & Margherita (2018); Cristoni & Tonelli (2018); Niero & Rivera (2018); Ormazabal et al. (2018); Verstraeten-Jochemsen et al. (2018)
	Manufacturing	M	
	Value-Creation Processes	M	
Product	Assets	M	Liu et al. (2022); Fletcher et al. (2021); Barletta et al. (2020); Ferreira et al. (2019); Garcia & Cayzer (2019); Prieto-Sandoval et al. (2019); Cristoni & Tonelli (2018); Romero & Molina (2014)
	Green Chemistry	R & M	
	Materials (Low Impact)	M	
	Resources	M	
	Reusability	R & M	
Strategy	Collaborations	R & M	Huang et al. (2022); Fletcher et al. (2021); Balestrucci (2020); Sari et al. (2021); Sehnem et al. (2020); Garcia & Cayzer (2019); Prieto-Sandoval et al. (2019); Cristoni & Tonelli (2018); Dubey et al. (2019); Niero & Rivera (2018); Despeisse et al. (2017); Zamfir et al. (2017)
	Leadership	M	
	Organization	M	
	Organizational Structure	R & M	
	Risk Management	M	
	Sustainability Strategy	M	
Technology	Data and Information	R & M	Huang et al. (2022); Fletcher et al. (2021); Martinsen et al. (2021); Balestrucci (2020); Barletta et al. (2020); Esmaeilian et al. (2020); Garcia & Cayzer (2019); Prieto-Sandoval et al. (2019); Braccini & Margherita (2018); Niero & Rivera (2018); Ormazabal et al. (2018); Despeisse et al. (2017); Zamfir et al. (2017)
	ICT and Analytic Tools	R & M	
	Information Systems	R & M	
	Infrastructure	R & M	
	Innovation	M	

(2018) conducted a case study to assess the role of life cycle sustainability considering CE. Their study focuses on BS 8001:2017 standards, which present a wide structure that connects the CE concept to a strategic map and is readjusted to a distinct maturity level of the business. Ormazabal et al. (2018) focused on CE in SMEs by developing empirical research to demonstrate that SMEs have a short-term vision depending on environmental management practices. Verstraeten-Jochemsen et al. (2018) developed a framework that considers the potential of research and development (R&D) to support CE implementations. Dubey et al. (2019) explored supplier relationship management practices for CE in a sustainable supply network under the influence of external pressures and top management commitment. Ferreira et al. (2019) conducted a cross-country analysis on the implementation and maturity of CE practices in the pulp and paper industries of Portugal and Spain.

Garcia & Cayzer's (2019) study concentrates on the readiness assessment of CE and proposes a framework that explores the enablers of CE in Colombia. Parida et al. (2019) developed a process model that describes how manufacturing firms, and their network of stakeholders orchestrate ecosystem-wide transformation towards the CE paradigm, including readiness assessment. Prieto-Sandoval et al. (2019) described key techniques that empower SMEs to build eco-innovations to achieve competitive advantage and to generate value creation compatible with the environment and capital that could favour the adoption of CE in SMEs. The framework of Sehnem et al.'s (2019) study is built on sustainable supply chain success with new operational excellence approaches. They integrate Upper Echelons Theory with critical success factors to analyse the adoption process of the maturity level of CE. Barletta et al. (2020) proposed an assessment tool for organizational readiness levels for manufacturing companies. Sari et al. (2021) established a corporate sustainability maturity model that can be implemented by organizations to perform self-assessments, define their existing stages of sustainability maturity, and transform them to mature sustainable organizations. Sehnem et al. (2020) performed a case study to examine the maturity of the implementation of CE procedures considering the CE business models.

2.2. Readiness and maturity models for industry 4.0

Smart manufacturing is enabled by the Industry 4.0 revolution, which systematically integrates production technology and advanced operations management to boost manufacturers' production efficiency, reduce energy usage, and lower prices by using more efficient

Table 3
Summary of dimensions and sub-dimensions of existing I4.0 Readiness and Maturity models.

DIMENSIONS	SUB-DIMENSIONS	LEVEL TYPE	REFERENCES
Economic	Finance Investments	R & M R & M	Bag & Pretorius (2020); Rauch et al. (2020); Ramanathan (2020); Maria et al. (2019); Mittal et al. (2018)
Environmental	Environmental Digital Eco-Systems Product Life Cycle	R & M R M	Liu et al. (2022); Dikhanbayeva et al. (2020); Ramanathan (2020); Maria et al. (2019); Schumacher et al. (2016)
Social	Culture Ecosystem Participants People Customers	R R & M R M	Elibal & Özceylan (2022); Huang et al. (2022); Liu et al. (2022); Naeem & Garengo (2022); Rafael et al. (2020); Ramanathan (2020); Rauch et al. (2020); Chonsawat & Sopadang (2019); Machado et al. (2019); Maria et al. (2019); Pirola et al. (2020); Schumacher et al. (2019); Akdil et al. (2018); Mittal et al. (2018); Sheen & Yang (2018); Despeisse et al. (2017); Schuh et al. (2017); Schumacher et al. (2016); Lichtblau et al. (2015); Schumacher (2015)
Policy	Regulations Standards Protection Governance	M M M M	Huang et al. (2022); Ramanathan (2020); Castelo-Branco et al. (2019); Ganzarain & Errasti (2016); Schumacher et al. (2016)
Process	Smart Operations Customers Manufacturing Value Creation Processes Process flexibility	R & M M M M R & M	Elibal & Özceylan (2022); Naeem & Garengo (2022); Dikhanbayeva et al. (2020); Ramanathan (2020); Rauch et al. (2020); Castelo-Branco et al. (2019); Chonsawat & Sopadang (2019); Pirola et al. (2020); Schumacher et al. (2019); Akdil et al. (2018); Mittal et al. (2018); Sheen & Yang (2018); Schumacher et al. (2016); Lichtblau et al. (2015); Schumacher (2015)
Product	Smart Marketing and Sales Operations Available Assets Flow of Material Product	R & M R & M M M	Liu et al. (2022); Naeem & Garengo (2022); Dikhanbayeva et al. (2020); Ramanathan (2020); Rauch et al. (2020); Castelo-Branco et al. (2019); Colli et al. (2019); Schumacher et al. (2019); Akdil et al. (2018); Schuh et al. (2017); Ganzarain & Errasti (2016); Schumacher et al. (2016); Lichtblau et al. (2015); Schumacher (2015)
Strategy	Digital strategy Innovation Management Organization Business Models Business and Organization Strategy Horizontal and Vertical Collaborations Corporate Standards Risk Management	R & M R R & M R M M M M	Elibal & Özceylan (2022); Huang et al. (2022); Naeem & Garengo (2022); Dikhanbayeva et al. (2020); Rafael et al. (2020); Ramanathan (2020); Rauch et al. (2020); Castelo-Branco et al. (2019); Chonsawat & Sopadang (2019); Colli et al. (2019); Machado et al. (2019); Pirola et al. (2020); Schumacher et al. (2019); Akdil et al. (2018); Mittal et al. (2018); Oleśków-Szłapka & Stachowiak (2018); Sheen & Yang (2018); Despeisse et al. (2017); Schuh et al. (2017); Ganzarain & Errasti (2016); Schumacher et al. (2016); Lichtblau et al. (2015); Schumacher (2015)
Technology	Data Security Data Usage Smart Products and Services Technology Technology Investments Data & Information Data-Driven Services Infrastructure Smart Operations	R R & M R & M R R M M M M	Elibal & Özceylan (2022); Liu et al. (2022); Huang et al. (2022); Naeem & Garengo (2022); Dikhanbayeva et al. (2020); Esmaeilian et al. (2020); Rafael et al. (2020); Ramanathan (2020); Castelo-Branco et al. (2019); Chonsawat & Sopadang (2019); Colli et al. (2019); Machado et al. (2019); Maria et al. (2019); Pacchini et al. (2019); Pirola et al. (2020); Schumacher et al. (2019); Akdil et al. (2018); Mittal et al. (2018); Oleśków-Szłapka & Stachowiak (2018); Despeisse et al. (2017); Schuh et al. (2017); Ganzarain & Errasti (2016); Leyh et al. (2016); Schumacher et al. (2016); Lichtblau et al. (2015); Schumacher (2015)

technologies and sustainable processes (Chonsawat & Sopadang, 2020). The adoption of I4.0 technologies is therefore an important topic addressed in the SME literature. For instance, Schumacher et al. (2015) established a model that assists businesses to self-assess their capacities in I4.0. Lichtblau et al. (2015) analysed the current situation of the businesses in the field of mechanical and plant engineering, focusing on what inspires and what obstructs them, and on the disparities that exist between SMEs and large enterprises. Their findings show a comprehensive systemic perspective of I4.0′s readiness in the field of engineering.

Ganzarain & Errasti (2016) proposed a three-stage process maturity model to guide and train SMEs to identify new opportunities for diversification within I4.0. Schumacher et al. (2016) proposed a maturity model for assessing I4.0 readiness and maturity levels of industrial enterprises in the field of manufacturing. Leyh et al. (2016) introduced the System Integration Maturity Model Industry 4.0, which allows an organization to identify the Information Technology (IT) system landscape with an emphasis on the criteria of I4.0. Schuh et al. (2017) proposed a six-stage maturity model that focuses on the four key structural areas of resources, information systems, organizational structure, and culture. Akdil et al.'s (2018) book chapter proposed a maturity model ideal for businesses preparing to transform for I4.0. Mittal et al. (2018) analysed currently available Smart Manufacturing and I4.0 maturity models from the point of view of SMEs. Oleśków-Szłapka & Stachowiak (2018) developed a framework for the Logistics 4.0 Maturity Model to provide businesses with an ability to determine the present state of Logistics 4.0 and to establish a road map for the continuous improvement.

Sheen & Yang (2018) performed a study to develop a readiness assessment tool that provides comprehensive requirements for SMEs. Castelo-Branco et al. (2019) conducted cross-country research to assess I4.0 readiness in manufacturing across EU (European Union) countries. Chonsawat & Sopadang (2019) defined a maturity model to assess Smart SMEs' readiness. Schumacher et al. (2019) presented a holistic procedure model on the maturity assessment of 65 critical success factors based on I4.0 aspects to guide manufacturing companies from their first contact with I4.0 until the definition of concrete action fields and their

Table 4
Roles of I4.0 Technologies in SCSC.

I4.0 TECH.	ROLE IN SCSC	REFERENCES
3D Printing	3D printing has been verified to be effective in enabling firms to adopt distributed production with environmental gains of that kind as better production system efficiency through reduced material consumption, greater material stability using recycled and repurposed materials as input for production with lower costs.	Garmulewicz et al. (2018); Despeisse et al. (2017); Van Wijk & Van Wijk (2015)
AR/VR/ Digital twin/ Simulation	AR lies between the physical world and virtual reality, enabling data to be acquired from simulations (e.g., digital twin-based real-time process optimization tool) to truly analyse real-world processes without displacing the real world. Digital twinning strengthen with AR and VR can be utilized to enhance interaction during disassembly operations, as well as help accelerate the flow of data for maintenance responses to maintain asset availability.	Romero et al. (2021); Rocca et al. (2020)
Robotics	Recycling will be more effective, efficient, and clean due to automated as well as smart robots. Sorting, cleaning recyclable materials, and disassembling robotics can operate over time. It implies that the recycling industry will be less exploited and safer.	Renteria & Alvarez-de-los-Mozos (2019); Sarc et al. (2019)
CPS	Smart waste collection systems relying on CPS combine cyber and physical areas to analyse, monitor, and interact with all aspects of waste management. The majority of CPS aspects rely on sensors, such as RFID, to track waste along with the waste management operation.	Ahmed et al. (2021)
Wi-Fi	Building SCSC by creating a marketplace that connects buyers and sellers of manufacturing services, raw materials, and products. By attributing the idea that so many objects will be linked to the internet, it is logical to anticipate that devices with the capability to wirelessly switch on/off, run a program, obtain information on power as well as water consumption, and so on will become increasingly common.	Sohal et al. (2022); Rossi et al. (2020); Asif et al. (2018)
Bluetooth/ Zigbee	Bluetooth/Zigbee technologies can fully replace the requirement for the internet to send data regarding deliveries to various areas of a plant, utilize less energy to interact throughout SCSC operations than internet-powered devices, and connect easily.	Sohal et al. (2022)
Barcode/ RFID	RFID technologies assist the waste and recycling management in tracing, work order management, and maintenance of waste containers, as well as operation validation and route control of waste vehicles in real-time, ensuring transparency as well as traceability.	Paul et al. (2022); Alves et al. (2021); Condemi et al. (2019)
IoT/Sensors/ NFC	Sensors and devices have long been used in the production field to increase productivity, discover, and inhibit errors before they exist, and remotely manage products. Checking the origins of resources guarantees long-term viability while also decreasing the effect of counterfeit components.	Alves et al. (2021); Cavalieri et al. (2021); Mboli et al. (2020); Ramadoss et al. (2018)
QR Code	In SCSC, QR codes are critical assets for managing inventory and production. Firms utilize QR codes to monitor far more than product names and pricing; they additionally monitor serial numbers, part numbers, lots and dates, and other data for the disposal phase.	Alves et al. (2021); Clark et al. (2020)
Edge/ Cloud Computing	Over the Internet, cloud computing makes it simple to connect servers, storage, databases, and a wide range of software solutions. Prior and present data can be utilized to forecast demand manage inventories, reduce waste as well as improve the sustainability of operations.	Sohal et al. (2022); Cavalieri et al. (2021)
Big Data Analytics	Big data features can be used to gain clarity for system integration and data exchange. Predictive models relying on historical and real-time data, according to the participants, can assist them in generating knowledgeable and dependable judgments.	Edwin Cheng et al. (2021); Del Giudice et al. (2020); Ramadoss et al. (2018)
AI/ML	Designers collaborating with AI may design CE-friendly products, parts, and materials. Given the pace with which an AI system can analyse vast volumes of data and recommend design plans or design revisions, AI can answer for superior designs quickly. AI can distinguish between dissimilar materials and recognize them despite dust or degradation using powerful visual technologies.	Chen et al. (2020); Jose et al. (2020); Ghoreishi & Happonen (2020); Ramadoss et al. (2018)
Blockchain	Blockchain is considered as the next emerging technology to accelerate SCSC implementation. Blockchain technology can improve CE by lowering transaction costs, improving supply chain performance and connectivity, ensuring human rights protection, improving healthcare patient privacy as well as wellbeing, and lowering carbon emissions.	Kayikci et al., 2022a; Kayikci et al., 2022b; Kayikci et al., 2021b
ERP/APS	ERP/APS provides various circularity-supporting technologies in its production and transportation domains that can assist businesses enhance their circularity adoption, such as Bill of Material (BOM), Material Requirements Planning (MRP).	Guo et al. (2022); Alarcón et al. (2021); Ivanov et al. (2021); Sarkis & Zhu (2008)
GPS/GPRS	Materials and goods can be tracked using GPS throughout their entire cycle.	Kouhizadeh et al. (2020)

realization. Colli et al. (2019) suggested a new approach for digital maturity assessment, based on the central elements of the Problem-Based Learning model. Machado et al. (2019) developed a study to assess digital readiness involving a self-checking tool. Their findings specify different levels of readiness and contrast between businesses, activities, and procedures to improve digitization. Maria et al. (2019) examined the effect of the economic, social, cultural, technological, and environmental dimensions on the readiness of I4.0. Naeem and Garengo (2022) investigated the interrelationships between I4.0 maturity of manufacturing processes and performance measurement and management in SMEs.

Pacchini et al. (2019) suggested a model to assess the degree of readiness of manufacturing companies concerning the adoption of I4.0 technologies. They developed an assessment structure based on the J4000 standard of the Society of Automotive Engineers to assess the application of lean manufacturing by Brazilian car parts manufacturers. Their assessment model consists of eight emerging technologies: IoT, Big Data, Cloud Computing, Cyber-Physical Systems, Collaborative Robots, Additive Manufacturing, Augmented Reality and Artificial Intelligence. Pirola et al. (2020) developed a detailed evaluation model for assessing the digital readiness levels of SMEs. They evaluated 20 manufacturing SMEs using the proposed model. Rauch et al. (2020) focused on I4.0 to develop an assessment model for SMEs to support strategy definitions and proposed a maturity level-based assessment tool. In addition, they implemented the assessment model in field research with 17 industrial firms. Dikhanbayeva et al. (2020) also studied I4.0 maturity assessments by classifying the main I4.0 design principles through the advancement of maturity models. Rafael et al. (2020) implemented a case study on SMEs to provide a maturity model for I4.0 adaptation with a specification focused on previously validated systems and technologies.

2.3. Readiness and maturity context for industry 4.0 and circular economy

In the literature review, I4.0 and CE concepts applied to formulate conceptualisations of SCSC have also been examined together. Although not explicitly addressing the concept of Smart Circularity, some studies combine I4.0 and CE to analyse smart and circular capabilities of organizations. Romero & Molina (2014) concentrated on Green Virtual Enterprise Breeding Environments to specify new sustainable industrial development maturity models to implement virtual industrial ecosystems contributing to the eco-restructuring of industrial processes and systems. They also explored different eco-industrial networking strategies for CE. Braccini & Margherita (2018) focused on guidelines for assessing projects' circularity and technology readiness levels. Abdul-Hamid et al. (2020) investigated how to prevent the difficulties of I4.0 in CE in the context of the palm oil industry using the fuzzy Delphi Method. Their conclusions show that the most critical difficulties are lack of automation system virtualization, the lack of clarity over economic benefits of digital investment, lack of process design, unstable connectivity among firms, and employment disruptions.

Bag & Pretorius (2020) conducted a literature review in the fields of I4.0, Sustainable Production, and CE, and further established a research structure demonstrating key sustainable manufacturing pathways. Bag et al. (2020) also concentrated on I4.0 and CE, using a survey to explore how I4.0 influences smart logistics and further influences competitive remanufacturing and green manufacturing potential, and the ultimate impact of these on logistics sustainability. Balestrucci (2020) conducted an explorative case study in a manufacturing company in the construction equipment industry to design a practical tool to facilitate the transition towards CE in connection with activities and strategies that can be applied in various market areas. The findings reveal a multi-readiness level model in four distinct fields, namely: Ecosystem of External Partners; Customer and Business model; Company's Culture and Internal Capabilities; and Design and Product Development. Yadav et al. (2020a) examined a distinctive series of Sustainable Supply Chain Management (SSCM) challenges and solution initiatives in a case study. Their research findings show that management and organizational difficulties and economic problems are the greatest challenges to the implementation of SSCM. Further findings establish priority approaches to developing effective business strategies to address SSCM implementation failures.

Piscitelli et al. (2020) reviewed the scientific literature relating to I4.0 and CE. Their findings show that CE displays great utilization potential in various industrial processes. However, CE potential cannot be achieved without I4.0, and conversely, I4.0 cannot be socially beneficial and sustainable without improving CE implementations. Ozkan-Ozen et al. (2020) concentrated on circular supply chains in the Industry 3.5 stage by identifying simultaneous barriers that combine circular supply chain and I4.0 challenges. Their findings indicate that the lack of information on data processing, lack of awareness of the decentralized corporate system for developing supplier partnerships, and lack of significant investments in I4.0 technology and circular strategies are the most significant obstacles for organizations initially. Dantas et al. (2021) conducted a comprehensive literature review to evaluate how the integration of I4.0 and CE can lead to the achievement of the SDGs. Kayikci et al. (2022c) analysed the drivers of smart and sustainable circular supply chain for reaching SDGs through stakeholder theory. Kayikci et al. (2021b) presented the concept of a SCSC for the achievement of SDGs for post-pandemic preparedness. Despeisse et al. (2017) suggested a research agenda to identify enablers and barriers for 3D printing associated with organizational capacity to perform CE from six subject perspectives, namely: design, supply chains, information flows, entrepreneurship, business models, and education. Esmaeilian et al. (2020) presented a review of blockchain technologies and I4.0 for the development of sustainable supply chains in the light of CE principles. Ramanathan's (2020) book chapter presents an integrated assessment framework for I4.0 readiness with a CE focus.

2.4. Research gap

The literature review above summarised shows that quite a few studies examine the readiness and/or maturity assessments of I4.0 and CE concepts, but none combine the two concepts together as a means to analyse SCSC readiness and maturity levels. This creates a significant gap in the literature, considering that a Gartner survey of 1374 supply chain leaders reveals that 70% of participants are planning to invest in the CE but only 12% have so far combined their digital and circular processes (Gartner, 2020). Such low percentage suggests that I4.0 is being overlooked in terms of the enabling role it plays as an essential driver of CE. For instance, I4.0 facilitates trace & track as well as real-time monitoring of the movement of products, by-products and waste flows. Such capabilities enable, for example, automated location and monitoring of natural capital and improve waste-to-resource matching in industrial symbiosis systems via real-time data gathering (Big Data) for improved resource management and decision making across various stages of the industry life cycle (Kristoffersen et al., 2020). This study addresses this imbalance by combining and integrating I4.0 and CE concepts into the SCSC concept in order to evaluate the readiness and maturity levels through a holistic assessment framework that will add to the current studies in the area.

3. Conceptual framework for the assessment of readiness and maturity level of SCSC

This paper proposes a conceptual approach for assessing SCSC readiness and maturity levels by performing a theoretically-focused literature review on SCSC. In addition, a practical case study supports the proposed framework (Pacchini et al., 2019; Collins & Hussey, 2007; Bryman, 1995). To develop the conceptual framework, an in-depth literature review was performed as the basis to conceptualise the core dimensions and sub-dimensions of current readiness and maturity models in the transition to I4.0 and CE, as summarised in Tables 2 and 3. The identified dimensions and sub-dimensions were conceptualised for SMEs following the SCSC concept, as described in Section 3.1 below, through a Delphi study involving selected industry experts. The study allowed the development of an assessment tool based on the conceptual model defined to measure the SCSC readiness and maturity level of SMEs.

3.1. Conceptualisation of literature review: Delphi study

To conceptualise the findings from the literature review for SMEs following the SCSC concept, a Delphi study was conducted following the process suggested by Kayikci et al. (2014). Fig. 3 illustrates the five steps of the Delphi study.

(i). *Data collection via literature review:* the existing dimensions and sub-dimensions from readiness and maturity models extracted from the literature review were gathered to use in the Delphi study. The studies selected during the literature review were examined separately under the headings of circularity and smartness to comply with the focus of this study as explained in Section 2.

(ii). *Expert selection:* an expert group was established, consisting of six selected senior experts: two academic professor experts in green supply chain and industrial engineering, two industry experts from consulting companies, one project manager from a research institution, and one expert from an industrial manufacturing association. The selected experts, with an average of seventeen years of experience, are all highly knowledgeable in the fields of CE, green supply chain, digitization, innovation, logistics, and transportation, and are well versed in the application of I4.0 and CE concepts to SMEs.

(iii). *First online roundtable* for determining dimensions: An open-ended questionnaire based on the dimensions identified (Tables 2 and 3) in the first round was prepared. The questionnaire included such questions as "*which dimensions are the most relevant for the assessment of SCSC readiness and maturity level of SMEs? Which dimensions should be taken out or which dimensions need to be added for readiness/maturity in transition to CE/I4.0 within the supply chain?*" The opinions of the experts were captured and measured on a five-point Likert scale (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree). A ranking of the dimensions was created and concluded by group consensus. The technology integration dimension was chosen to address smartness perspectives when selecting dimensions. The economic, environmental, and social dimensions were added as the three pillars of sustainability, linked with the circularity perspective in this study. Apart from this, dimensions frequently used in the literature and thus suitable for the study were adapted and incorporated. Since government policies, products, production processes and organizational strategies play a significant role in the process of becoming smarter and more circular, dimensions of policy, process, product, and strategy were also added to complement the set of relevant dimensions. After completing the first-round discussions, the above-mentioned eight dimensions were determined (Tables 2 and 3).

(iv). *Second online roundtable* for determining sub-dimensions: For the second round, another open-ended questionnaire was prepared with the created tables for sub-dimensions, and included such questions as "*which sub-dimensions are the most relevant for the assessment of SCSC readiness and maturity level of SMEs? Which sub-dimensions should be taken out or which dimensions need to be added for readiness/maturity in transition to CE/I4.0 within the supply chain and under which relevant dimensions they should be summed up?*". The same procedures were performed to set the sub-dimensions by group consensus. After completing the second-round discussions, 117 sub-dimensions were determined.

(v). *Construction of the readiness and maturity framework*: after determining the eight dimensions and 117 sub-dimensions for readiness and maturity for circularity and smartness through two online round table discussions, the framework shown in Fig. 4 and Table 5 was defined.

3.2. Assessment of readiness and maturity framework for I4.0 and CE

To assess the SCSC readiness and maturity level, a six-point evaluation tool was used based on Grant & Pennypacker (2006). This evaluation was performed by identifying six answers to each statement ranging from non-existent (level0) to executed (level1), managed (level2), established (level3), predictable (level4) and optimised (level5). Then, a survey was prepared using the dimensions and sub-dimensions obtained from the proposed conceptual framework. The survey was used to gather the individual opinion of experts for the assessment of SCSC readiness and maturity framework and the answers were analysed according to the Readiness and Maturity Index Score of SCSC, shown in Fig. 4.

The assessment first begins with the calculation of Equation (1), Equation (2), Equation (3) and Equation (4). With these calculations, the values of the quadrants I, II, III and IV in Fig. 4 were obtained. The

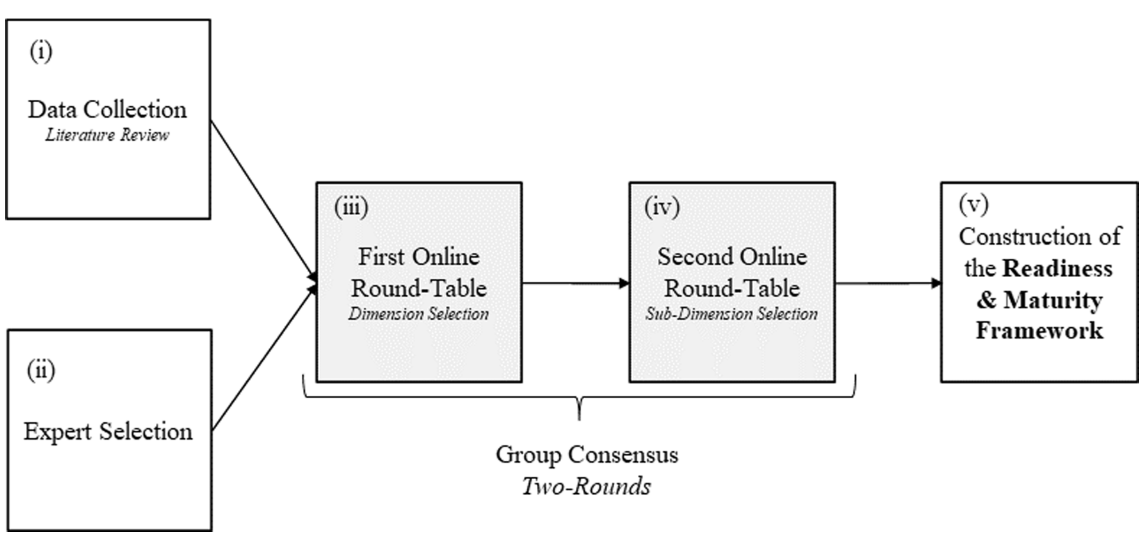

Fig. 3. Conceptualisation of Literature Review through Delphi-Study.

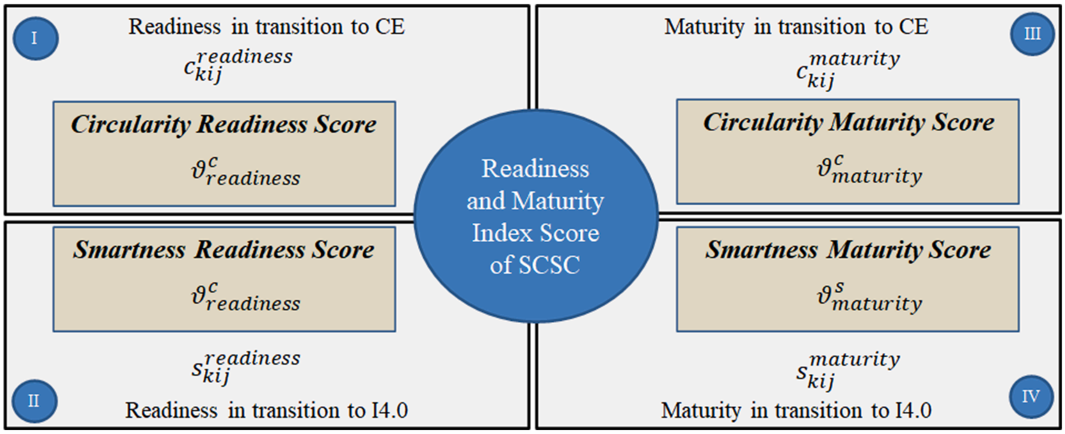

Fig. 4. Readiness and Maturity Index Score of SCSC.

specific variable notations are described as below.

Equation (1) shows the formula for $\vartheta^{c}_{readiness}$. When calculating this formula, the values given by each firm to the sub-dimension of each dimension for $c_{kij}^{readiness}$ are summed. Then, this sum is divided by the company (k) and multiplied by the total number of sub-dimensions created to measure ϑ_{scsc}. This process is also calculated for.

$s_{kij}^{readiness}$, $c_{kij}^{maturity}$ and $s_{kij}^{maturity}$ as seen inEquations (2), (3) and (4), respectively.

$$\vartheta^{c}_{readiness} = \left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} c_{kij}^{readiness}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{1}$$

$$\vartheta^{s}_{readiness} = \left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} s_{kij}^{readiness}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{2}$$

$$\vartheta^{c}_{maturity} = \left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} c_{kij}^{maturity}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{3}$$

$$\vartheta^{s}_{maturity} = \left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} s_{kij}^{maturity}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{4}$$

Readiness and maturity index of SCSC can be calculated using the following formula in Equation (5), which computes ϑ_{scsc} as the average of the calculated score indexes.

$$\vartheta_{scsc} = \frac{1}{4}\left(\vartheta^{c}_{readiness} + \vartheta^{s}_{readiness} + \vartheta^{c}_{maturity} + \vartheta^{s}_{maturity}\right) \tag{5}$$

$\vartheta_{readiness}$ and $\vartheta_{maturity}$ values are calculated as according to the following Equations (6), (7) and (8).

$$\vartheta_{readiness} = \frac{1}{2}\left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} c_{kij}^{readiness}}{r \times \sum_{i=1}^{m} n_i} + \frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} s_{kij}^{readiness}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{6}$$

$$\vartheta_{maturity} = \frac{1}{2}\left(\frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} c_{kij}^{maturity}}{r \times \sum_{i=1}^{m} n_i} + \frac{\sum_{k=1}^{r}\sum_{i=1}^{m}\sum_{j=1}^{n} s_{kij}^{maturity}}{r \times \sum_{i=1}^{m} n_i}\right) \tag{7}$$

$$\vartheta_{scsc} = \frac{1}{2}\left(\vartheta_{readiness} + \vartheta_{maturity}\right) \tag{8}$$

4. Case study

The proposed framework was implemented in a case study involving SMEs in the textile sector. This sector was selected for two main reasons. The first is related to sustainability; the textile sector is responsible for serious environmental impacts, and hence, there is significant room for improvement through CE. The second reason is that in the textile industry, there are great opportunities for increased efficiency, effectiveness, and productivity through implementing I4.0. Hence, the SMEs in the textile sector should consider the transformation to I4.0 and CE simultaneously.

The questionnaire prepared for this study was applied to 4 different companies at different levels of readiness and maturity, and at different tiers of the textile supply chain in terms of CE and I4.0 technologies. Four different companies were chosen to compare each company's level of both readiness and maturity levels in CE and I4.0 technologies under a single framework which was also used to detect deficiencies. The four companies at different tiers of the supply chain can reveal the different levels of readiness and maturity in the textile value chain concerning the adoption of CE and I4.0 technologies. Such multi-tiered approach also helps to create a uniform supply chain level throughout the entire supply chain. The case study was applied in the Turkey's textile sector, in companies located in Izmir.

In 2017, the total annual consumption of textile products by households in the EU27, Norway, Switzerland, Turkey and the United Kingdom was estimated as 13 million tons (Manshoven et al., 2019). The textile industry pollutes the oceans with microfibers in textile waste (Kazancoglu et al., 2020a). The amounts of textile waste have increased globally and recycling or reusing textile products has been recommended to reduce new wastes from virgin materials (Dahlbo et al., 2017). Therefore, this industry is a field with high environmental and social impact potential, which includes extremely long, complex, and difficult supply chain processes (Jacometti, 2019). Indeed, the European Commission has identified textiles, apparel and fabrics, as a priority product category within a CE (Manshoven et al., 2019; EC, 2019). For this purpose, in order to study the I4.0 dimension of the closed-loop supply chain in the textile industry, CE implementation is aimed to replace the linear economy.

There are some fields of garment and textile processing where I4.0 is already in existence (Küsters et al., 2017). RFID tags are applied in fibre cones utilized in knitting machines (Simonis et al., 2016). Most textile industries, however, comprise SMEs with scarce resources and facing challenges related to financial assets, IT infrastructure and qualified staff (Horváth & Szabó, 2019; Rauch et al., 2019).

Systems theory, the theoretical background of this research, approaches organizations as living organisms, and acknowledges these relations. Systems theory also aims at simplifying the complex organizational structures by identifying the stakeholders and their specific relationships. This paper positions the stakeholders in a closed-loop supply chain in textiles, as shown in Fig. 5. The textile supply chain includes four stakeholders, which are retailers, brand owners, garment manufacturers, and material converters (Kazancoglu et al., 2020b; Cao et al., 2008). According to the cradle-to-cradle concept, the life cycle of the product starts from the design stage (Kazancoglu et al., 2020b) before continuing with fibre manufacturers, yarn manufacturers, fabric

Table 5
Proposed Conceptual Framework for Smart Circular Supply Chain Readiness and Maturity Levels.

DIMENSIONS	CE		I4.0	
	READINESS SUB-DIMENSIONS	MATURITY SUB-DIMENSIONS	READINESS SUB-DIMENSIONS	MATURITY SUB-DIMENSIONS
Economic	• Green & Circular Economic Potential (Solid Waste and Landfill Quantities) Financial Capability for Circular Investments	• Business Sustainability Economic Benefit Return on Asset Investment Deposition Efficiency (Solid Waste and Landfill Quantities)	• Financial Resource Capability Digital Business Potential (Anticipated Productivity Gains) Digital Business Potential (Revenue Growth)	• Investment Intensity in I4.0 technologies Return on Digital Investment Digital Agility
Environmental	• Eco Industrial Parks Environmental Commitment Potential of Industrial Symbiosis (Recovery, reuse and recycling of industrial residuals) Closed-Loop/Open-Loop Network Design (availability of up-front network development) Energy Consumption Awareness	• CO_2 Emissions Level (GHG Emissions) Eco-Efficiency Energy Consumption Green Labeling Industrial Waste Water Reuse and Recycling Effectiveness of Industrial Symbiosis Sustainable Product & Process Design	• Digital Eco-Systems Digital Capabilities for Environmental Challenges	• Digital Product Life Cycle Integration of Digital Technologies with Environmental Sustainability
Social	• Ecosystem Participants Individual Behaviour of employees Society/ Customers Willingness Work Culture & Social Perceptions Circular Competences of Employees	• Ethical Behaviour Labor Practices Society/ Customers Acceptance Work Culture	• ICT Competences of Employees Cultural Acceptance (Knowledge sharing etc.) Employee Willingness to Use New Technologies	• Digital Access and Interaction with Customers Digital Adaptation of Employees
Policy	• Statement of Corporate Sustainability Policy Govermental Regulations Govermental Incentives	• Development of Corporate Sustainability Policy Effective Governance Regulations and Standards for the Circular Economy	• Regulations on Data Security and Sharing Protection of Intellectual Property Governmental Incentives on Digitization	• Labour Regulations for I4.0 Standards for Digital Technologies Effective Digital Governance
Process	• Life Cycle Assessment for Circularity Circular Value & Co-Creation Processes Reverse Operations	• Circular Phases of End-of-Life Cycle Circular Manufacturing Systems Closed-Loop Supply Chains	• Process Flexibility Flexible Manufacturing Systems Automation in Manufacturing Supply Chain Network Design and Integration	• Process Responsiveness Digital Manufacturing Systems (Production Technology Integration) Digital Supply Chain Management (Visibility, Traceability and Flexibility)
Product	• Availability of Circular Product Design Presence of Green & Circular Materials	• Equipments for circular operations Green Chemistry (the design of products and processes that minimise or eliminate the use and generation of hazardous substances.) Environmental Impact Assessment Extension of Product Life Cycle	• Modular Design Mass Customisation Potential Automation in Warehouse and Transportation	• Digital Product Configuration Digitization in Warehouse and Transportation Digitalization of Sales/ Services (Servitisation)
Strategy	• Horizontal Cooperations Vertical Cooperations Adaptiveness of Organizational Structure Leadership (Support of Top Management) Commitment to Sustainability and Circular Economy	• Horizontal Collaborations Vertical Collaborations Circular Organizational Structure Risk and Resilience Management Sustainable Circular Vision and Strategy	• Sustainable Development Goals Horizontal Integration Potential Vertical Integration Potential Value of ICT in company Digital Strategy Road-Map Digital Risk management	• Horizontal Integration Level Vertical Integration Level Digital Corporate Culture Digital Strategy Deployment Digital Business Model Digital Resilience
Technology	• Data and Information Infrastructure for Circular Business Model Research and Development Activities	• ICT and Analytic Tools Information Systems Circular and Eco-Innovation Digital Equipment & Infrastructure Innovation Potential and The Development of CE Strategic Capabilities	• Basic ICT Infrastructure Requirements Digital Process Visualization Technological Systems Integration (existing)	• Digital Technology Investment Smart Factory Level Intelligent Connectivity Cyber Physical Systems

manufacturers and garment manufacturers. Supply and process take place before the manufacturing process. Products are designed so that post-user and post-production fibres can be utilized as raw materials in combination with virgin fibres (Kazancoglu et al., 2020b). Distribution is provided by continuing the process with brands and retailers. The user phase, which is the last process before connecting to the circular, is also completed by the end user. The closed-loop starts with the collectors, after the remaining textile waste has been obtained from the end user. Wastes are sorted during the collecting process. Non-usable parts are discarded and recycled for use as raw materials (Georgise et al., 2014; Jia et al., 2020; Kazancoglu et al., 2020b; Pandit et al., 2019; Rossi et al., 2020; Sauvé et al., 2016; Sharma et al., 2019; Frederick, 2010). As seen in Table 6, four supply chain stages were considered to represent different tiers of the supply chain studied: fibre manufacturer, yarn manufacturer, fabric manufacturer and garment manufacturer.

To ensure the accuracy of the results, four companies were selected which are already implementing either one or both the I4.0 and CE concepts, and therefore have the necessary basic knowledge and understanding of their core concepts. The I4.0 and CE developments of these companies are shown in Table 6. They are expert textile companies

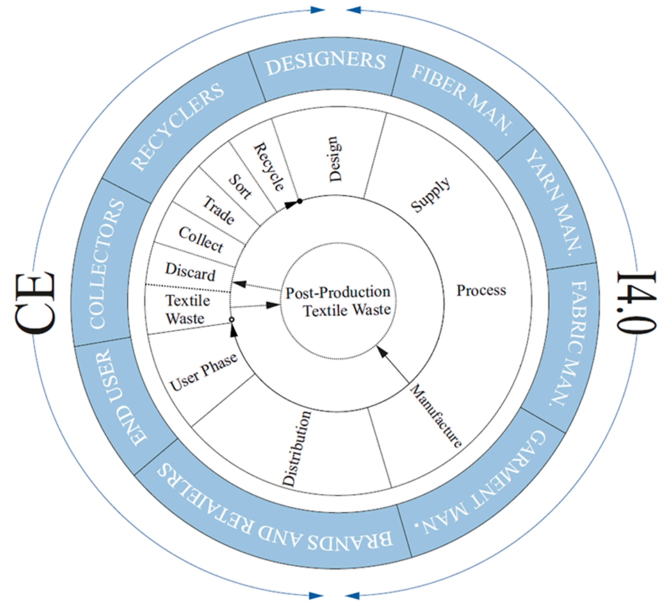

Fig. 5. Closed-loop supply chain of textile industry with stakeholders, adopted from Kazancoglu et al. (2020a) and Kazancoglu et al. (2020b).

Table 6
Demographic Structures of the Companies.

	CE	I4.0	Supply Chain Stage	Scale
Company 1	Readiness	Readiness	Fibre	Small
Company 2	Readiness	Maturity	Yarn	Medium
Company 3	Maturity	Readiness	Fabric	Medium
Company 4	Maturity	Maturity	Garment	Large

in Turkey, with large experience and well versed in I4.0 and CE implementation with a minimum of five, and an average of ten years working experience, and an average of seven managed projects each.

5. Result

This section provides the results and discusses the readiness and maturity levels of the SMEs considered in the study. The framework model provides a straightforward tool for the analysis of level differences across the key readiness and maturity dimensions considered in this study. As seen in Fig. 6, the average readiness and maturity indexes of the four SMEs in the supply chain studied present clear differences around the key dimensions.

More specifically, when all three SCSC scores (readiness, maturity and combined readiness & maturity) are considered among the dimensions, clear differences in values are observed. Within the scope of readiness, scores range from 1.3 (the lowest value) in the policy dimension to 2.4 (the highest value) in the product dimension. However, within the scope of the maturity, the lowest value was calculated as process dimension with 2.5; the highest value is environmental with 3.2. Within the scope of readiness and maturity combined, the lowest and highest values are policy (2.0) and product (2.7), respectively.

Additionally, Fig. 7 shows the radar chart for readiness and maturity dimensions in terms of I4.0 and CE concepts. In this respect, some dimensions present identical values in average scores while other dimensions show a "more mature" or "more ready" levels. For example, for the economic dimension, the maturity score in I4.0 appears to be the highest, while the readiness scores for CE and for I4.0 values are identical. There are no overlapping scores for the environmental dimension. For the social dimension, the highest value is in the CE maturity score. In addition, the maturity score of I4.0 is lower than the readiness score for CE. According to these values, companies appear more socially ready for CE applications than for I4.0 applications.

For the policy dimension, CE appears to be more mature. The sequence differs in the process dimension once again, and the maturity score for I4.0, which shares the same value with the readiness score for CE, which corresponds to the highest value for the dimension. The product dimension is similar to the process dimension within the scope of maturity score for I4.0 and readiness score for CE values. The results also show that the maturity scores calculated for I4.0 and CE concepts are the highest values for the strategic dimension, with the CE score suggesting better preparedness than I4.0 in the strategy dimension for the readiness perspective.

In the technology dimension, the readiness score of I4.0 has a significantly lower value. However, the proximity of readiness and maturity score for CE values shows a narrowing difference between companies in terms of CE. The dimension with the highest readiness score for CE is the product, while the lowest CE readiness value is in the policy dimension. Moreover, the readiness score for I4.0 has the lowest overall score. In contrast, the maturity score for CE reaches the highest level in the policy dimension, and the lowest in the process dimension. For the maturity score for I4.0, the highest level is in the environmental dimension, while the policy dimension presents the lowest maturity level for I4.0. The biggest difference between readiness and maturity score under CE is in the policy dimension, while the smallest difference is in the strategic and technology dimensions. In addition, the biggest difference between readiness and maturity score for I4.0 is in the environmental dimension, while the smallest is in the social dimension.

These results reveal original findings of the study. As explained in the introduction and literature sections, this proposed model is different from the previous studies in many ways. First of all, in this proposed model, readiness and maturity models can be measured within the same assessment model, unlike in other studies. Another aspect that differs from other studies is that by referring to both I4.0 and CE perspectives within the SCSC concept, the 'smart circular' part of the supply chain can be evaluated. Furthermore, the topic under consideration may be investigated from multiple angles with the aid of a radar chart reflecting the research findings. Overall, the differences between the readiness and maturity scores of key organizational dimensions in I4.0 and CE scopes can also be observed in a practical fashion.

6. Discussion

It is important to integrate smart technologies and the concept of circularity into the supply chain for effective and sustainable management in areas such as production and sales performance of SMEs, energy use, price management. However, this integration remains a challenge for the SMEs because most are only able to focus on one of these concepts due to the economic challenges and inadequacy of the resources. Therefore, this paper mainly addresses the readiness and the maturity level of the SMEs for the integration of the SCSC notion. The existing literature related to the readiness and maturity level studies generally focuses on only one of these two complementary aspects.

Many studies in the literature focus on readiness and maturity level in terms of CE and I4.0 technologies however, a comprehensive approach is missing. For instance, Basl & Doucek (2019) evaluated and summarized the available readiness indexes and maturity models for "4.0" developments, with an emphasis on Industry 4.0, especially in European countries. Aiming to provide a guideline in a related field, this study developed a framework by examining, summarizing, and comparing the basic qualities of this notion and incorporating them into a metamodel. Chonsawat & Sopadang's (2020) main objective is to create readiness indicators to support and assess SMEs' transition to Industry 4. Thus, their aim was to create I4.0 readiness indicators for SMEs in order to assess their preparedness and assist decision-makers in selecting the critical dimensions to integrate I4.0 in their organization for value creation. Grufman et al. (2020) examined I4.0 in terms of

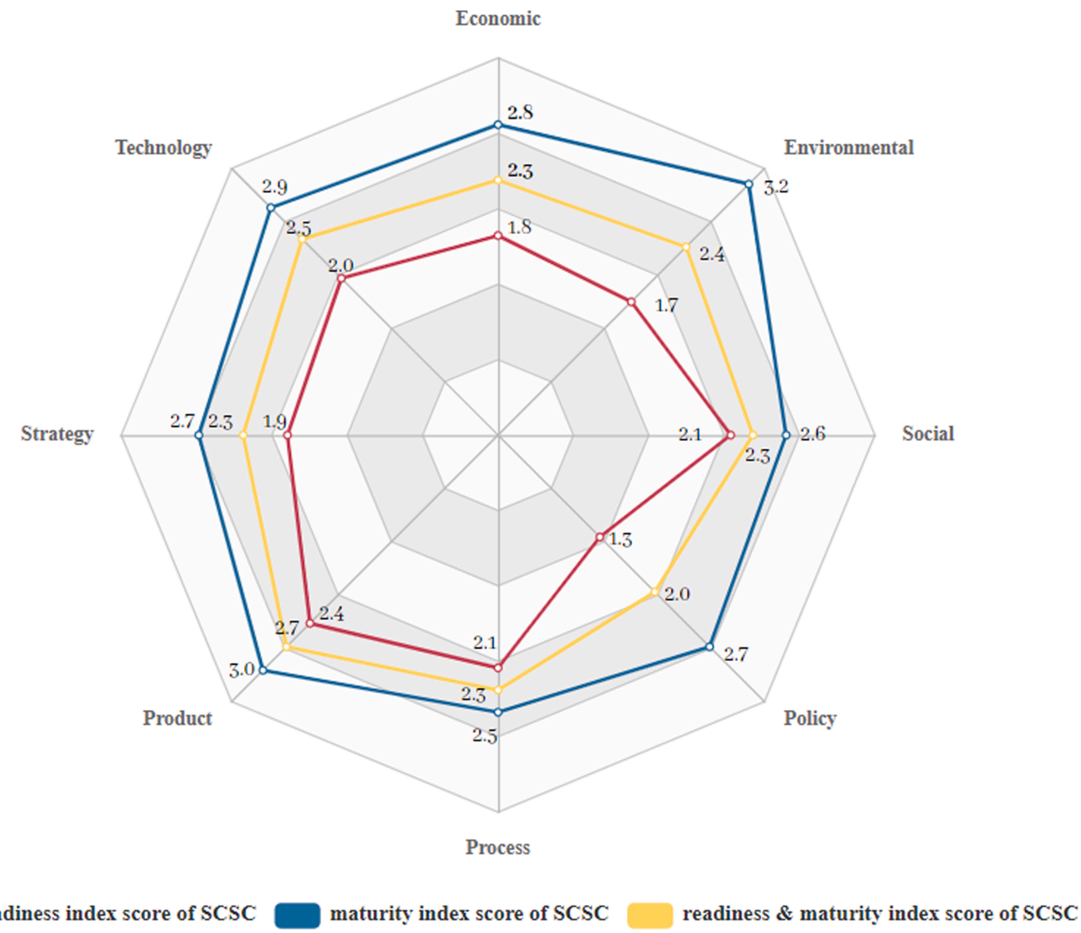

Fig. 6. Radar chart for SCSC readiness & maturity dimensions.

SMEs, including its potential and problems, as well as SMEs' readiness for I4.0. Furthermore, Jesus & Lima (2020) studied the determinants that contribute to the development of specific maturity models developed for specific conditions and contexts, and that can address both the need for self-diagnosis of readiness and the actions that aim to achieve a progressive reconfiguration guided by continuous improvement toward I4.0. Awan et al. (2021) aimed to identify the goals and expectations of I4.0 stakeholders in terms of how the IoT potential for governing the CE and concluded by identifying various IoT tools for dealing with CE challenges as part of best practices.

The transition to the CE enabled by I4.0 necessitates a better understanding of government, suppliers, international organizational interests, and expectations. Further studies such as the one by Sacco et al. (2021) introduced the Circularity and Maturity Firm-Level Assessment Tool (CM-FLAT) to measure CE maturity, i.e., the presence of defined activities and practices building the groundwork for CE implementation, and circularity, i.e., achieving CE-related performances. Moreover, Brendzel-Skowera (2021) developed a bottom-up approach for applying the CE concept by evaluating the organizational maturity of businesses in terms of implementing CE concepts.

The main findings of this study relate to the readiness and maturity level of SMEs from different dimensions, by for instance, revealing the economic dimension as having the highest maturity score in I4.0. Moreover, the readiness score of CE and I4.0 technologies have identical importance in SMEs. From an environmental perspective, there are no overlapping scores. When investigating the social dimension, we observe that the highest score belongs to the CE maturity score. Furthermore, the maturity level for I4.0 is lower than the readiness value for CE. Also, CE seems to be more advanced in the policy dimension.

7. Implications

In terms of theoretical implications, it is not enough for a company to simply reach a certain level in the supply chain for a successful I4.0 and CE transition. This transition requires similar efforts across supply chain stakeholders. From a systems theory perspective, which forms the theoretical background of this research, organizations are influenced by their external environments. In this respect, variations of readiness and maturity levels concerning I4.0 and CE adoption by firms in the supply chain are likely to influence further adoptions by suppliers and buyer organizations in different supply chain tiers. In this context, the relationships and interconnections between supply chain actors is of fundamental importance. Therefore, regardless of how ready or mature the company is, it is important that the company involved in the supply chain attempts to reach the same level as other stakeholders. To this end, carefully monitoring of the level of other stakeholders is essential for the simultaneous transformations across the entire supply chain in what concerns I4.0 and CE adoption.

In terms of practical implications, the framework proposed in this study provides a practical tool for companies to analyse their readiness and maturity levels of I4.0 and CE. The framework also supports analysis at multi-tier levels, allowing measurement of stakeholders at different stages of the supply chain. Measuring these levels allows companies to monitor stakeholders in their supply chains and manage their relationships, because a problem arising from the multi-tier of a large company may affect other companies in the supply chain. In this case, larger companies should support smaller companies' efforts to reduce the problems arising from other stakeholders in the supply chain and strive to bring all supply chain tiers to the same level. In this context, this study provides valuable insight into the readiness and maturity scores of

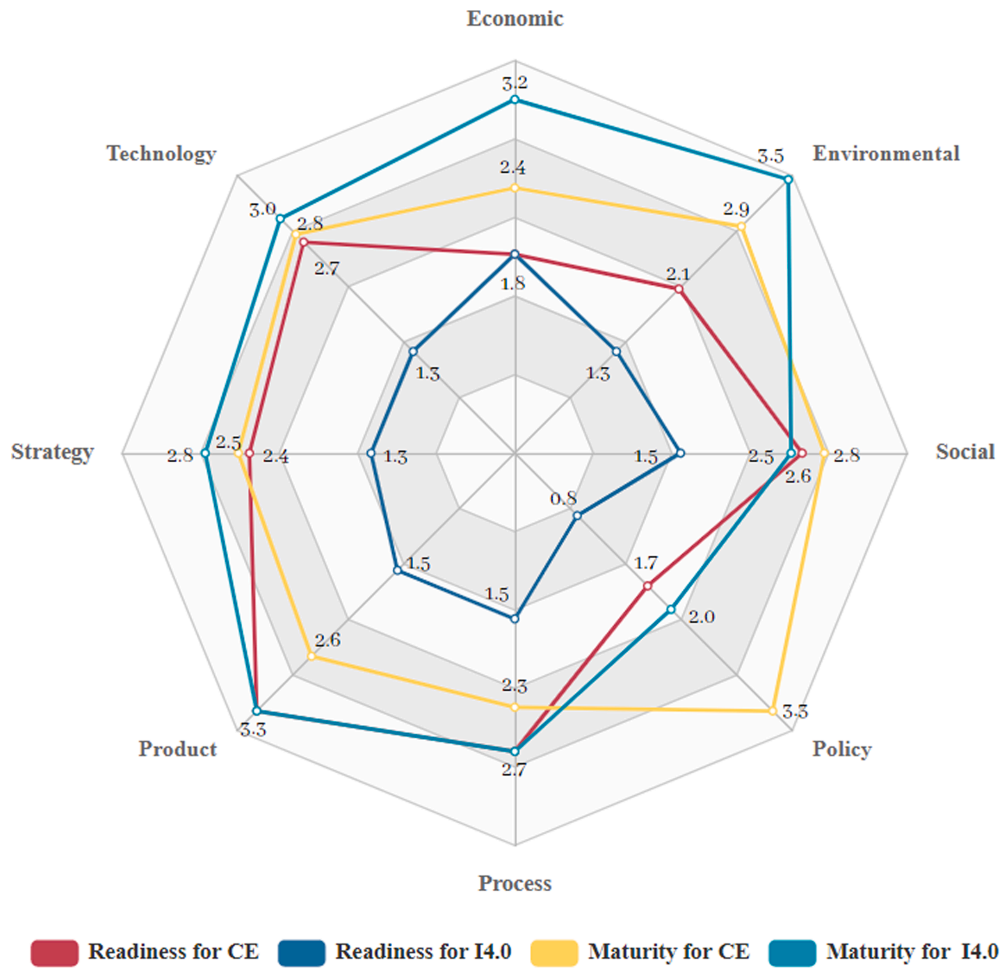

Fig. 7. Radar chart for readiness & maturity dimensions of I4.0 and CE.

multiple stakeholders in the textile industry. These scores need to be brought to similar levels throughout the entire supply chain for smoother relationships between the supply chain and the operations. Otherwise, inequality and problems between this operation and related organizations will affect the entire supply chain.

In terms of managerial implications, the readiness and maturity levels provide important value references that can be connected with balanced scorecards to support strategic performance management concerning I4.0 and CE adoption. In this context, readiness and maturity levels can provide helpful information in relation to risk management, as large differences in terms of readiness and maturity for I4.0 and CE suggest potential relationship problems between buyer–supplier dyads. Apart from these, readiness and maturity levels also allow a firm to determine its financial stage and investment plans, such as budgeting, and investment. Human resources and operations management are the other areas that can be guided by readiness and maturity level results. From another perspective, these levels also have great importance to policymakers making efforts to increase the efficiency of firms in I4.0 or CE. However, the incentives, rules, and regulations are currently made at firm level, but since all stakeholders in the supply chain should be at the same level, these incentives, rules, and regulations should be made at supply chain level. In this context, this conceptual framework guides policymakers to get the necessary actions on a supply chain instance.

8. Conclusion

With the rising population, the value of CE in the utilization of scarce resources grows continually. Therefore, transition into a circular model of the economy has become a requirement. The purpose of this study is the evaluation of both readiness and maturity level for I4.0 and CE perspectives in SMEs. For a successful CE or I4.0 transition, reaching a certain level in the supply chain is not sufficient. Regardless of how ready or mature the firm is, it should also be at the same level as other stakeholders in the supply chain. Multi-dimensions encompassing the whole supply chain were included in the development of the proposed framework for determining the readiness and maturity levels of SMEs regarding I4.0 and CE in the supply chain as the systems theory suggests. The development of the readiness and maturity model for both I4.0 and CE can be considered as the major contribution of this study. This study examined the ecosystem participants of the supply chains (e.g., stakeholders) and their multi-tier perspectives to present a holistic perspective of the supply chain. This is the first study to assess both the readiness and maturity level of I4.0 and CE in the supply chain. The main limitation is that it was applied to only four companies in the same supply chain ecosystem, although these were specifically selected based on their different levels of readiness and maturity. For that reason, in the future, a larger number of companies from the same and also from the different supply chain ecosystems can be elaborated in order to obtain more comprehensive results and implications. This study can be further strengthened by presenting some other real-life cases. In this context, the reasons for the lack of readiness and maturity of SMEs to incorporate CE and I4.0 technologies can be investigated in further studies. After finding the indicators, multi-criteria decision-making methods can be employed for SMEs to overcome these challenges and draw inferences. The presented framework can be further developed to investigate the digital and circular readiness and maturity for the SMEs' supply chains to achieve SDGs. Furthermore, the theoretical background of this study can be elaborated by integrating further management theories to support this framework. As a future work, the proposed framework can be applied in a larger study with the participation of more stakeholders or in other industrial sectors.

CRediT authorship contribution statement

Yasanur Kayikci: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Yigit Kazancoglu:** Writing – review & editing, Resources, Investigation, Data curation. **Nazlican Gozacan-Chase:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Cisem Lafci:** Writing – original draft, Visualization, Methodology, Data curation. **Luciano Batista:** Supervision, Resources.

Declaration of Competing Interest

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

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