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Empowering supply chains with Industry 4.0 technologies to face megatrends

Elena Pessot[1,2] | Andrea Zangiacomi[2] | Irene Marchiori[2] | Rosanna Fornasiero[3]

[1]Department of Information Engineering and Mathematics, University of Siena, Siena, Italy

[2]STIIMA-CNR, Institute of Intelligent Industrial Systems and Technologies for Advanced Manufacturing – National Research Council of Italy, Milan, Italy

[3]IEIIT-CNR, National Research Council, Padua, Italy

Correspondence
Andrea Zangiacomi, STIIMA-CNR, Institute of Intelligent Industrial Systems and Technologies for Advanced Manufacturing – National Research Council of Italy, Milan, Italy.
Email: andrea.zangiacomi@stiima.cnr.it

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Abstract

This paper investigates how current megatrends (i.e., aging population, growing urbanization, shifts in consumer demands, geopolitical shifts, depletion of natural resources, climate change) are changing the supply chain landscape and the role of Industry 4.0 (I4.0) technologies to support alignment with these changes. Building on contingency theory, the study employs focus-group interviews with various experts to generate new insights into fitting supply chain capabilities and enabling technologies. Data collected in the focus groups helped us to identify five supply chain capabilities as prevalent and mostly fitting the external contingencies, i.e., customer-driven, urban-centered, resource-efficient, fast reactive, and human-centered supply chain. Moreover, this study highlights and compares the potential of I4.0 technologies and their applications in supporting specific supply chain capabilities. The findings of this study can inform supply chain managers in the definition of capabilities to be enhanced at the supply chain level and contribute toward understanding the extent of I4.0 technologies in empowering supply chains to face turbulent and changing conditions.

KEYWORDS

contingency theory, external context, focus group, Industry 4.0, supply chain capabilities, supply chain management

INTRODUCTION

Supply chains operate under an increasingly global, complex, and uncertain context, challenging their abilities to adapt and convincingly address the dynamics caused by megatrends (Christopher & Holweg, 2011; Ramezani & Camarinha-Matos, 2020). Aging population, depletion of resources, and growing urbanization are examples of megatrends that have a major impact on companies with the rise of different challenges (Gunasekaran et al., 2015; Rajesh, 2017). Thus, managers must rethink supply chains (Kalaitzi et al., 2021) and identify success potentials to meet competitiveness (Ben-Daya et al., 2017; Ivanov & Dolgui, 2020). Beyond creating new business models, specific capabilities are required to focus on reorganizing value creation with partners in the up- and downstream network (Bienhaus & Haddud, 2018). Specifically, supply chains need to develop a set of capabilities to "organize, deploy and control all the necessary investments, assets, resources, routines, processes, and systems" to enable resilience (Brusset & Teller, 2017).

The innovation and improvement of supply chain capabilities can be supported by applying technologies if guided by appropriate strategic value drivers. In this sense, the transformation driven by the growing adoption of Industry 4.0 (I4.0) technologies represents an opportunity to be leveraged by supply chains (Ivanov et al., 2019). I4.0 is based on automation, communication, and data-exchange enhancement, where different digital technologies can help connect and integrate physical devices, intelligent machines, and human resources at the factory level and being extended to the overall supply chain (Hofmann et al., 2019; Oesterreich & Teuteberg, 2016). The adoption of I4.0 technologies at the supply chain level is argued to increase visibility, risk diversification, higher demand responsiveness, and personalization, with shorter lead times, better capacity utilization and flexibility, and improved transparency and communication among supply chain partners (Hofmann & Rüsch, 2017; Ivanov et al., 2019).

There is a growing number of scholarly and practitioner contributions on how I4.0 technologies are changing the supply chain and offering tremendous opportunities for more efficient and effective supply chain management (Ben-Daya et al., 2017; Hofmann et al., 2019). Nevertheless, several companies are still lagging in transforming operational processes driven by I4.0 solutions, especially concerning connectivity and integration with other companies (Hahn, 2020; Hofmann et al., 2019). There is still the need to identify a systematic approach to I4.0 implementation addressing the specific megatrends (Gružauskas et al., 2018), characterizing the current environment, and linking the application of technologies not only to the efficiency of processes but also to the capabilities developed at the supply chain level. Prajogo et al. (2018) proposed a contingency model linking the business environment and supply chain strategies, concluding that technological changes should be considered a key dimension affecting supply chains. However, there is a lack of studies that thoroughly analyze how I4.0 technologies can enhance specific supply chain capabilities in addressing the megatrends characterizing the external environment.

Companies could leverage I4.0 to achieve strategic objectives but may lack a clear understanding of long-term benefits and changes in approaching its implementation as well as capability enhancement (Chiarini et al., 2020; Ralston & Blackhurst, 2020; Zangiacomi et al., 2020). Moreover, despite the growing interest in the context of the application of I4.0 technologies in supply chains, a lack of frameworks and roadmaps that include clear guidelines and the implementation of digital tools to address supply chain challenges is highlighted by scholars, e.g., Büyüközkan and Göçer (2018).

Based on these gaps, two research questions were developed and guided the study:

RQ1. Given the current megatrends changing the supply chain landscape, what should be the prevalent supply chain capabilities to align with these changes?

RQ2. To what extent can I4.0 technologies support the supply chain capabilities identified to face these challenges?

This paper aims to investigate the opportunities offered by I4.0 in empowering supply chains to face the challenges derived from the megatrends that are changing the supply chain landscape. Grounding on contingency theory (Donaldson, 2001; Lawrence & Lorsch, 1967), this study explores the prevalence of supply chain capabilities in better fitting the external contingencies represented by these megatrends (Prajogo et al., 2018). The contingency view was adopted to understand how to tailor the supply chain capabilities to changing megatrends as contextual (or contingency) variables. Moreover, among traditional contingency factors, technology plays a promising role (Victer, 2020), and the I4.0 technologies to facilitate capabilities were studied accordingly.

To this extent, we believe this work can offer practitioner and scholarly impact. While past research has dug deep into I4.0 technologies at the factory level, our study offers insight into specific supply chain capabilities and sheds light on how technologies can empower them while facing challenges arising from megatrends. Arguing that companies should invest in technology based on the trends that will most affect their business and supply chains, the study examines key aspects of I4.0 technologies in supply chain processes and ideally generates prescriptive insights.

This article is structured as follows. The next section is dedicated to the theoretical background, i.e., it describes the most important megatrends, followed by a review of studies on the concepts of supply chain capabilities and on I4.0 technologies and their applications in supply chain management. The third section describes the adopted methodology, i.e., the focus group interviews with experts. The qualitative results from the analysis of the focus group discussions are presented and further discussed in the fifth section. We conclude the article with a summary of the contributions and limitations, drawing suggestions for future research.

THEORETICAL BACKGROUND

Megatrends affecting the supply chain landscape

The global context is characterized by relevant trends that can be considered external sources of change affecting the current and future supply chain landscape, raising new challenges that need to be recognized and faced effectively (Ramezani & Camarinha-Matos, 2020).

In this work, we focus on a set of megatrends among the ones reported in the literature, highlighting their future projections and possible impact on supply chain processes in the following years (Kalaitzi et al., 2021). The trends considered were retrieved from the analysis of several works at the scientific and industrial levels considering geopolitical, social, economic, and environmental aspects (as shown in Table 1).

TABLE 1 Most relevant megatrends (and supporting evidence/related projections) affecting supply chain landscape.

Megatrends	Projections	References	Impact on supply chains
Aging population	In 2050, there will be more than 1.5 billion people aged 65+ years (2020: 727 million) and 3.2 million aged 100+	Roland Berger (2020), United Nations (2020)	Supply chain labor/talent
	Need for a lifelong learning mindset, digital and human-centric skills, and new emerging roles for manufacturing	BCG (2021), WEF (2019), WMF (2019)	Supply chain labor/talent
Growing urbanization	Urban areas and megacities • By 2050, two-thirds of the global population will live in urban areas, resulting in more congested cities. • Moreover, by 2030, the world is projected to have 43 megacities, mainly in developing regions	ESPAS (2019), United Nations (2020)	Logistics and manufacturing operations
	Smart cities • Widening of smart cities with up to 80% of miles traveled in urban areas through shared autonomous vehicles by 2040. • More than 4 billion connected IoT devices in commercial smart buildings by 2028	Deloitte (2021), McKinsey (2018)	Logistics and manufacturing operations
Shifts in consumer demands	More compelling personalization requirements: 71% of consumers expect personalized interactions	Capgemini (2022), McKinsey (2021)	Logistics and manufacturing operations
	Growth in design and production of solutions by consumers or by small factories/FabLabs located nearby	Deloitte (2021), Herrmann et al. (2020)	Logistics and manufacturing operations
Geopolitical shifts	Growth of nationalism, separatisms, terrorist attacks, border security enforcement: • In EU more than 50,000 individuals are monitored for radical potential. • Number of wars could exceed 40 ongoing conflicts per year	ESPAS (2019), Roland Berger (2020)	Logistics and manufacturing operations, risk management, sourcing decisions
	New geographical and economic barriers among countries: trade barriers, barriers due to the COVID-19 pandemic, sanctions, and stalling trade agreements	Roland Berger (2020)	Logistics and manufacturing operations, sourcing decisions
Depletion of natural resources	Resource scarcity and consumption • Larger amount of population facing water and food scarcity • By 2050 global water demand will increase by 32% compared to 2015	Roland Berger (2020), United Nations (2020)	Logistics and manufacturing operations, sourcing decisions
	Critical and rare materials • 30 raw materials identified as critical by EU • By 2050 the demand for rare earths could increase tenfold. The EU will require 60 times more lithium for e-mobility and 15 times more cobalt for electric car batteries	Roland Berger (2020)	Sourcing decisions
	Energy consumption • In 2050, fossil fuels could still top the energy mix • Energy consumption will rise globally by 1.7% per year	ESPAS (2019), Roland Berger (2020)	Sourcing decisions
Climate change	• By 2030, the world will be 1.5 degrees warmer than during pre-industrial times Intensification of natural disasters • By 2100, up to six simultaneous hazards could impact some tropical coastal areas • Weather-climate disasters cost 290 billion euros in 2017	ESPAS (2019), Mora et al. (2018), Roland Berger (2020)	Supply chain risk management, logistics, and manufacturing operations

One relevant trend for future concerns over demographic change is related to the aging population. The number of people over 65 years is foreseen to double, from 727 million in 2020 to 1.5 billion in 2050. Moreover, there will be 3.2 million people over 100 years old. This will lead to the need for a lifelong learning mindset and demand for digital and human-centric skills, also due to new emerging roles for manufacturing (BCG, 2021; WEF, 2019; WMF, 2019). The prominent growth of urbanization, with 68% or two-thirds of the global population living in urban areas by 2050, will represent another significant trend. Together with the concurrent emergence of megacities with a projection of 43 by 2030, especially in developing countries, this will imply more substantial amounts of goods and people moving along even more congested streets. Conversely, many cities are financing projects on improving people's quality of life as well as cities' sustainability, efficiency, and safety with innovation and new technologies based on smart infrastructures (Li et al., 2018; McKinsey, 2018). According to projections, by 2028, there will be more than 4 billion connected IoT devices in smart commercial buildings and by 2040 up to 80% of passenger miles traveled in urban areas will be in shared autonomous vehicles (Deloitte, 2021).

Concerning the shifts in consumer demands trend, consumers are becoming more oriented to satisfy personalization requirements, with 71% of them expecting companies to deliver personalized interactions (McKinsey, 2021), which will have an impact on logistics and manufacturing operations levels. This trend also concerns the establishment of the "do it yourself" (DIY) paradigm, which is forcing companies to rethink their supply chain configurations to provide consumers with accessibility to reliable tools for design and production at home or in small factories and FabLabs in urban areas (Deloitte, 2021; Herrmann et al., 2020).

Over the next few years, the growth of nationalism, separatisms, terrorist attacks, and border security enforcements could affect the geopolitical shift (Roland Berger, 2020). For example, in Europe, more than 50,000 people are currently being monitored for radical potential, and war (civil or intrastate) could result in over 40 conflicts per year (ESPAS, 2019). Moreover, new geographical and economic barriers such as trade and other barriers among countries due to the COVID-19 pandemic will emerge together with sanctions and stalling trade agreements with impacts at multiple supply chain levels (Roland Berger, 2020).

Two main trends can be reported in regard to environmental concerns. The first, the depletion of natural resources, is characterized by issues such as water and food scarcity, which will affect a more significant amount of the population in several countries (United Nations, 2020), with an increase by 2050 in global water demand by 32% compared with 2015 (Roland Berger, 2020). Energy consumption will also rise globally by 1.7% per year due to increasing residential and industrial energy demands (ESPAS, 2019), together with the need for limited raw materials, like rare-earth elements, to manufacture electronic items, thus severely affecting sourcing decisions. In particular, the demand for rare earths could increase tenfold by 2050, and the EU will require 60 times more lithium for e-mobility and 15 times more cobalt for electric car batteries. In total, 30 raw materials or raw material groups were identified as critical (Roland Berger, 2020). The other relevant trend is climate change, with a forecasted heart temperature increase of 1.5 degrees by 2030 compared with pre-industrial times (Roland Berger, 2020). Projections on the intensification of natural disasters report that, by 2100, up to six simultaneous hazards will have an impact on some tropical coastal areas (Mora et al., 2018). In total, weather-climate disasters cost 290 billion euros in 2017 (ESPAS, 2019). The COVID-19 pandemic, with several millions of confirmed cases, forced social distancing to contain the contagion and the shutdown of whole sectors of the economy, with severe interruptions of global supply chains. These disruptions caused difficulties in logistics and production management, forcing supply chains to implement actions to mitigate related effects and deal with additional impediments and delays in reaching suppliers and customers.

Supply chains must take into account the dynamics characterizing these changing conditions in order to successfully align their strategies and related capabilities to the external context and to improve overall supply chain performance (Goldin, 2014; Simangunsong et al., 2012; Wagner & Bode, 2008).

Supply chain capabilities and technology support to fit with the external context

According to contingency theory, organizations configure their structure and strategy to maintain fit with changing contextual factors to attain high performance (Donaldson, 2001). Thus, there is no "one best way" to manage and organize single companies and supply chains, as different contextual (or contingency) variables require different approaches (Lawrence & Lorsch, 1967; von Falkenhausen et al., 2019). Companies and supply chains must identify reactive and proactive actions to face the external context they operate and understand the degree of fit in terms of interaction between strategies and contextual variables (Venkatraman, 1989). The fit between the external infrastructures and strategic orientation can particularly affect financial and market performance (Chan et al., 2000). For example, Lee (2002) analyzed the impact of external uncertainty in terms of supply (stable versus evolving processes) and demand (functional versus innovative products) and defined a path to align the supply chain to the changing market, proposing strategies that utilize risk-hedging, responsiveness, and agility.

Moreover, the literature shows the importance of adopting technologies (in particular IT, e-commerce, and digital) to support the strategic fit: IT advancement and IT alignment can facilitate the development of supply chain capabilities (Ralston & Blackhurst, 2020; Wu et al., 2006) and can have an interactive effect between the customer and supplier integration (Chan et al., 2000; Devaraj et al., 2007). In particular, "supply chain capabilities refer to the ability of an organization to identify, utilize, and assimilate both internal and external resources/information to facilitate the entire supply chain activities" (Wu et al., 2006). Supply chain capabilities probably represent a higher level in the hierarchy of organizational capabilities (Grant, 1996). These capabilities embrace the dimensions of information exchange, coordination, interfirm activity integration, and supply chain responsiveness, thus reflecting the ability to perform all cross-functional as well as interorganizational activities to face environmental changes (Wu et al., 2006; Zangiacomi et al., 2017).

However, it must also be stated that capabilities are typically developed due to the strategy and structure fit; as such, companies and thus the supply chain can achieve a competitive advantage (Chen, 2019; Stock et al., 1998). In this sense, supply chain capabilities can be ascribed to the response variables that the overall supply chain should pursue to maximize effectiveness in facing contextual (or contingency) variables (Sousa & Voss, 2008; von Falkenhausen et al., 2019). Specifically, supply chain capabilities to withstand uncertainties and contingent challenges are mainly studied in terms of resilience (e.g., Bhamra et al., 2011; Brusset & Teller, 2017; Zsidisin & Wagner, 2010), with the need to further widen this concept to take into consideration specific external megatrends causing instability.

In addition, technology is changing these capabilities, and strategic supply chain management is expected to adapt, integrate, and reconfigure internal and external resources, skills, and functional competencies to cope with the changing environment pushed by contingency factors (Felsberger et al., 2020). Nowadays, I4.0 and smart systems hold interfirm processes whose interaction supports the supply chain in mitigating actual disruptions and proactively avoiding possible future issues while enabling resilience (Ivanov et al., 2019; Ralston & Blackhurst, 2020). A particular concern has been focused on how data analytics capabilities can be applied to predict future and identify real-time events (Ivanov & Dolgui, 2020).

I4.0 enabling technologies in supply chains

I4.0 is conceptualized as the digital transformation of business environments, thanks to the adoption of information and automation technologies that facilitate integration among machinery, products, and operational processes within and between supply chain actors (Ivanov et al., 2019; Oesterreich & Teuteberg, 2016). The underlying principle of I4.0, leading to a paradigm shift in processes and industries, especially manufacturing, toward the so-called Fourth Industrial Revolution, is the decentralization and interconnectedness of systems that autonomously self-adapt and interact within intelligent networks (Fatorachian & Kazemi, 2020; Xu et al., 2018). The concept has attracted considerable attention from the 2011 initiative by the German federal government, which coined the term "Industrie 4.0," now supported by many funding programs and research initiatives in European and worldwide countries under different labels (Chiarini et al., 2020; Oesterreich & Teuteberg, 2016).

To accomplish such transformation and digitize firm processes, a growing set of enabling technologies, principles, and management systems fall under the unifying concept of I4.0 (Ardito et al., 2018; Chiarini et al., 2020). Current I4.0 models are primarily focused on production processes. Still, they have disruptive, transformative effects also on the up- and downstream value chains (Asdecker & Felch, 2018), generating network effects across industries (Büyüközkan & Göçer, 2018). As stressed by Fatorachian and Kazemi (2020), I4.0 and related technologies can create integrated and end-to-end supply chains characterized by a high level of connectivity, transparency, autonomy, collaboration, and flexibility from suppliers to final customers. This extends to the consumer value creation and co-creation process by adopting several digital technologies that support all customer journey phases (Matarazzo et al., 2020).

Companies could leverage I4.0 to achieve strategic objectives but may lack a clear understanding of long-term benefits and disruptive changes in approaching its implementation as well as capability enhancement or higher risks exposure (Chiarini et al., 2020; Ralston & Blackhurst, 2020; Zangiacomi et al., 2020). Different researchers thus underline the central role of customer needs and value creation as well as supply chain resilience in embedding I4.0 to enable technologies in supply chain management, with supply chain goals that are not changed but can be achieved differently (Oh, 2019; Zangiacomi et al., 2020).

In this sense, big data analytics (BDA) enable extracting relevant knowledge for better forecasting the demand and replenishment quantity, thus improving service and delivery levels, lowering procurement costs, reducing inventories, variability and stock-outs, and identifying risks (Ardito et al., 2018; Erevelles et al., 2016; Hofmann & Rüsch, 2017; Kache & Seuring, 2017; Tiwari et al., 2018). The Internet of Things (IoT) allows real-time acquisition and collection of raw operational data, tracking, and more accurate information-sharing across the supply chain (Abdel-Basset et al., 2018; Ardito et al., 2018; Ben-Daya et al., 2017; Dalmarco & Barros, 2018; Garrido-Hidalgo et al., 2019).

The application of cloud-based computer systems in the supply chain permits companies to store raw data in structured information to be remotely accessed and exchanged in real-time between supply chain management and other functions or across supply chain actors (Ardito et al., 2018; Bienhaus & Haddud, 2018; Hofmann & Rüsch, 2017; Mai et al., 2016; Xing et al., 2016). Beyond these technologies considered at the basis of I4.0, other enabling solutions can be included under the label of I4.0 in a broader sense (Hofmann & Rüsch, 2017), as they fit technological, organizational, and industrial requirements of reaching a better quality, efficiency, and increased productivity (da Silva et al., 2018). For example, Gružauskas et al. (2018) integrate autonomous vehicles, which are used in transportation and operations to reduce costs, emissions, lead time, and damaged products, with cyber-physical systems and BDA and IoT to gather, process, and utilize information in supply chains more efficiently. Robots are mainly adopted in production lines for hazardous or labor-intensive activities and distribution centers (Dalmarco & Barros, 2018). Artificial intelligence (AI) includes multiple subtechnologies such as machine learning, deep learning, natural language processing (NLP), and strong AI. It plays a central role in autonomous systems, robots, and data science (Baryannis et al., 2019; Li et al., 2017; Rodríguez-Espíndola et al., 2020). Regarding distribution ledger and blockchain, they enable a reduction in information disruption risk and assure better quality of information, trust, and transparency for distributed contract collaboration (Ivanov et al., 2019; Min, 2019).

The complete list of technologies that can be included under the label of "I4.0 enabling technologies," with related definitions and applications in supply chains and their management, is listed in Table 2.

Despite growing interest in the context of the digital supply chain, a lack of frameworks and roadmaps that include clear guidelines and the implementation of tools to address supply chain problems is highlighted by scholars such as Büyüközkan and Göçer (2018). Dalmarco and Barros (2018) reviewed I4.0 technologies for supply chains and application examples, arguing that each company's initiative enhances the supply chain's competitive advantage in adopting the technologies and collaboratively and safely sharing useful information for integration of the whole supply chain. Recently, Shao et al. (2020) proposed a four-stage framework for wide supply chain implementation of I4.0, adopting advanced technologies and organizational enablers of interaction among supply chain actors. The trigger stage is represented by the visualization level, followed by the level 1 linkage and connected supply chain. The final stage relates to the smart supply chain, depicting a self-adaptive system able to take corrective measures.

Other contributions studied the adoption of I4.0 technologies and their impacts on specific areas or dimensions of the supply chain (e.g., Asdecker & Felch, 2018; Ben-Daya et al., 2017; Bienhaus & Haddud, 2018). For what concerns the specific role of I4.0 technologies in facing different sources of instability, Das et al. (2019) analyze methodologies to mitigate and recover the supply chain disruptions and related ripple effects. In particular, BDA, advanced trace and tracking systems, and blockchain technology can support tracing the roots of disruptions (Dolgui et al., 2018). Moreover, additive manufacturing (AM) moderates disruption propagation in the supply chain, thus reducing related layers (Ivanov et al., 2019).

Along the same line, Ivanov et al. (2019) developed a framework for mutual analysis of I4.0 technologies in the supply chain and disruption risk effects, which may cause structural dynamics and the ripple effect. The authors consider five types of disruption risks: external risk (e.g., fire accidents, natural catastrophes, economic downturn, legal disputes, and strikes); demand disruption risk; supply disruption risk (e.g., price fluctuations, unstable quality); time risk related to delays in supply chain processes; and information disruption risk. Ralston and Blackhurst (2020) reported that smart systems could improve supply chain resilience and performance and act as enhancers to deal with unexpected events in terms of performance and resilience.

In the attempt to link the relevant megatrends considered, the supply chain capabilities required, and the role of I4.0 technologies in supporting them according to a contingency view, Figure 1 summarizes the main themes discussed in this section and the reasoning underpinning the study.

METHODOLOGY

This study employs focus-group research as a qualitative approach to gain a deeper understanding, pursue new and emerging ideas, and share visions to inform future decision-making (Morgan, 1997) on possible capabilities and technologies for supply chains aiming to address current megatrends. The technique of focus-group interviews, in which key informants interact and uncover

TABLE 2 I4.0 enabling technologies for supply chains.

Technology	Definition and examples of subtechnologies	Applications in SC management
Autonomous transport systems	Machines capable of sensing their navigation and acting without human input. They include autonomous vehicles and drones	Use in transportation and operations for reducing costs, emissions, lead time, and damaged products (Bechtsis et al., 2018; Gružauskas et al., 2018)
Robots	In I4.0, robots play a collaborative and autonomous role. Collaborative robots physically interact with human operators and other robots in intuitive self-learning environments, and autonomous robots are capable of operating without human-assistance and/or interaction, sometimes integrated with artificial intelligence	Adoption in production lines for hazardous or labor-intensive activities and in distribution centers (Bogataj et al., 2019; Dalmarco & Barros, 2018)
Artificial intelligence	A branch of computer science concerned with the automation of intelligent behavior such as perception, reasoning, recognition, understanding, communication, design, thinking, and learning, which can be realized artificially by machine, system, or network	Central role in autonomous systems, robots, and data science. AI includes multiple subtechnologies such as machine learning, deep learning, natural language processing (NLP) and strong artificial intelligence (Baryannis et al., 2019; Li et al., 2017; Rodríguez-Espíndola et al., 2020; Zuo et al., 2018)
Cloud-based computer systems	They allow multiple, remote access to, and use of data and software available through networks. Subtechnologies include infrastructure and services, i.e., platform as a service (PaaS), software as a service (SaaS), business process as a service (BPaaS), and infrastructure as a service (IaaS)	Signaling and storing raw data in structured information to be remotely accessed and exchanged in real time between SC management and other functions or across SC actors (Ardito et al., 2018; Bienhaus & Haddud, 2018; Hofmann & Rüsch, 2017; Kaasinen et al., 2020; Simeone et al., 2018; Xing et al., 2016)
Internet of things	It encompasses the digital interconnection of a network of physical objects that can turn into "smart things" through the integration of a series of subtechnologies as sensor technologies, machine to machine (M2M) communication, cyber-physical systems (integrating physical and virtual world), process intelligence, until digital twin	It allows real-time acquisition and collection of raw operational data, tracking and more accurate information sharing across the SC (Abdel-Basset et al., 2018; Ardito et al., 2018; Ben-Daya et al., 2017; Dalmarco & Barros, 2018; Garrido-Hidalgo et al., 2019)
Distributed ledger/ blockchain	Distributed, public ledger, which is collectively kept up to date according to strict rules and general agreement, providing full security for information storage and communication	Reduction in information disruption risk, better quality of information, trust and transparency for distributed contract collaboration (Ivanov et al., 2019; Min, 2019)
Big data analytics	Gathering and extraction of large quantities of data into a historical and real-time data set to be analyzed with tools and statistical methods supporting real-time cyber decision-making. Included subtechnologies and techniques are the ones of data storage, simulation, and optimization	Enable extracting relevant knowledge for better forecasting the demand and replenishment quantity, improving service and delivery levels, lowering procurement costs, reducing inventories, variability, and stock-outs, identifying risks (Ardito et al., 2018; Dubey et al., 2018; Hofmann & Rüsch, 2017; Kache & Seuring, 2017; Tiwari et al., 2018)
Mobile and wearable devices	Mobile and wearable devices' technologies that can be embedded in other devices and can act autonomously for performing specific functions	Support in expensive, labor-intensive process (Hao & Helo, 2017; pwC, 2016)
Communication infrastructure	ICT networks and protocols are the backbone of the other I4.0 technologies, for establishing viable communication among devices and people	Direct communication for alignment of consumption and production, and between SC partners (Ben-Daya et al., 2017; Hazra et al., 2020; Hofmann & Rüsch, 2017)
Identification and location technologies	Complementary technologies for real-time information acquiring, and identifying goods and process execution. Examples of identification technologies include QR code, any NFC including radio frequency identification (RFID) and barcode tags; location technologies include GPS trackers, GPS tracking systems, and wireless indoor positioning systems	They support transparency and real-time identification and traceability, with better data quality (Bienhaus & Haddud, 2018; Ivanov et al., 2019; Özdamar & Ertem, 2015)

(Continues)

TABLE 2 (Continued)

Technology	Definition and examples of subtechnologies	Applications in SC management
Visual computing	It refers to the entire field of acquiring, analyzing, and synthetizing visual data (embedding in or extracting information from images) through visual tools. It comprises the subtechnologies of augmented reality (AR), virtual reality (VR), and computer vision	It allows the creation of a visual representation of the production systems and the interactions with SC partners for testing solutions, mitigating problems, and training of managers and operators (Dalmarco & Barros, 2018; Rejeb et al., 2020; Roldán et al., 2019)
Additive manufacturing	Set of technologies to print 3D CAD models in different materials (e.g., metal, wax, plastics, and ceramics), layer upon layer. It enables the production of mechanical parts that could not be fabricated through regular processes. Examples of technologies include 3D printing and hybrid manufacturing	Production of lighter and cheaper parts than other production technologies, with implications on the choice of suppliers and personalized production (Dalmarco & Barros, 2018; Rodríguez-Espindola et al., 2020; Thomas, 2015)

arguments supporting each other's perspective, has been recently adopted in supply chain management literature to generate richer and fresher insights into important issues (e.g., Chekurov et al., 2018; Murfield & Esper, 2016; Sweeney et al., 2018).

For this study, five semistructured focus group interviews have been organized and subdivided into two sets (described in Session 1 and Session 2). A protocol for planning and conducting the focus groups was specifically developed (Murfield & Esper, 2016), including the participants' sampling; the size, number, and composition of groups; the choice of the moderators; and the research objectives and procedures (i.e., the time constraints and questions to be asked) (Morgan, 1997).

First, the focus groups in both sessions ranged between five and seven participants, including representatives of different industries, with different roles along the supply chain and people from universities and research centers. We sought heterogeneity in participants to probe different perspectives and avoid cycles of responses dominating the discussion, with observations limited to adoption of kinds of supply chain or technologies that are more peculiar to some sectors, or affected by specific competitive dynamics, or exposure to external instabilities.

Second, moderators were selected based on their knowledge of the study's objectives and their ability to create an environment that was conducive to a group discussion, where all members could have the opportunity to express their idea without restrictions (Krueger & Casey, 2015; Onwuegbuzie et al., 2009). Specifically, each group was facilitated by one member of the research team and one independent practitioner (with primary competencies in supply chain management or strategy). The moderators were prepared to effectively stimulate each participant's involvement and active intervention while avoiding possible negative dynamics, such as dominant personalities, coalitions, and communication problems (Krueger & Casey, 2015; Zeng et al., 2019).

Third, the study was designed first to introduce the general topic, followed by questions to engage the participants (Krueger & Casey, 2015) and orient the discussion to obtain results of different group interviews comparable with the others (Chekurov et al., 2018). Figure 2 shows the research design and the protocol of the focus groups, further described in this section.

Planning and organization of the focus groups

We conducted the three focus groups of Session 1 at a professional conference focused on supply chain management and I4.0, held in Portugal in June 2018. These

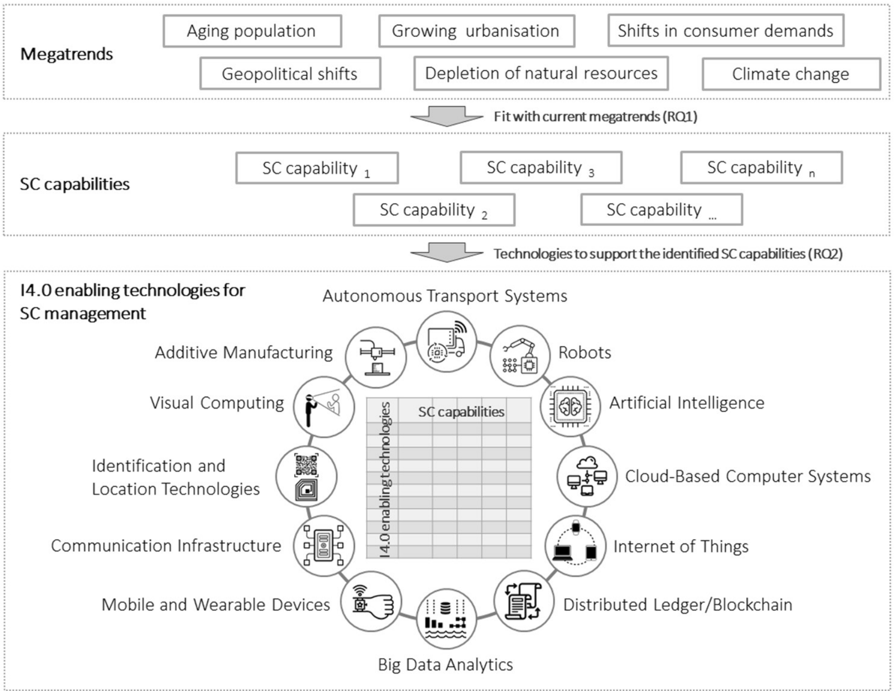


FIGURE 1 Framework proposing the links between megatrends, supply chain capabilities, and I4.0 enabling technologies.

three focus groups were mainly aimed at gaining a deeper understanding of the possible supply chain capabilities needed to face current megatrends and collecting initial insights into the processes and enabling technologies to shape them. Key informants on the research team mailing list and the conference co-organizers were invited, aiming to involve experts in the field of supply chains and I4.0-enabling technologies, mixed by professional backgrounds (Krueger & Casey, 2015). The first set of focus groups in Portugal included 20 people from 17 organizations. Table 3 provides the participant characteristics.

At the beginning of Session 1, the research group introduced the main features of current megatrends and their impacts on the supply chain (based on Table 1), with some examples from the literature on well-known organizations facing the described challenges. Among them was the increasing rate of catastrophic natural disasters, such as the Japanese earthquake and tsunami in 2011, which led motor vehicle manufacturers such as Toyota, Nissan, and Honda to create alternative manufacturing capabilities and locate multiple sources for parts. The questions formulated in Session 1 were: *How should supply chain capabilities be defined to face these megatrends? What are possible requirements and needs in terms of processes and supply chains?*

We conducted the other two focus groups in a professional conference on digital transformation of European society and industry in Austria in December 2018. This second session of focus groups was developed from the insights and themes discussed in the first session (Murfield & Esper, 2016), further informed by the literature on supply chain management, to probe into both research questions. Specifically, it aimed to confirm or expand data already gathered on supply chain capabilities and collect and share ideas on the enabling I4.0 technologies. The two focus groups in Austria had 11 participants from 10 organizations, with characteristics as shown in Table 4.

In the introduction for Session 2, the research team presented the supply chain capabilities identified in the first session, and examples from the literature on well-known uses of I4.0 technologies in some supply chain dimensions (e.g., production) were highlighted. For instance, Adidas was cited among the pioneers of 3D printing in the footwear industry, with innovative and fully customized products and shoes directly manufactured from CAD models to respond to growth of the DIY trend. Next, questions were formulated as follows: Which of these I4.0 technologies should be implemented to enhance *the identified supply chain capabilities? What are their possible applications?*

Both sessions lasted 45 min and were composed of a brief introduction (5 min), parallel working focus group discussions (30 min), and wrap-up and conclusions (10 min). After introducing the questions, the participants were divided into groups, each joined by the two moderators. Specifically, one practitioner played the role of the facilitator, while one member of the research team was in charge of taking notes. Each group was equipped with an empty poster to write down the viewpoints and answers to the sessions' questions expressed by each participant and emerged during the internal discussion. In Session 1, the

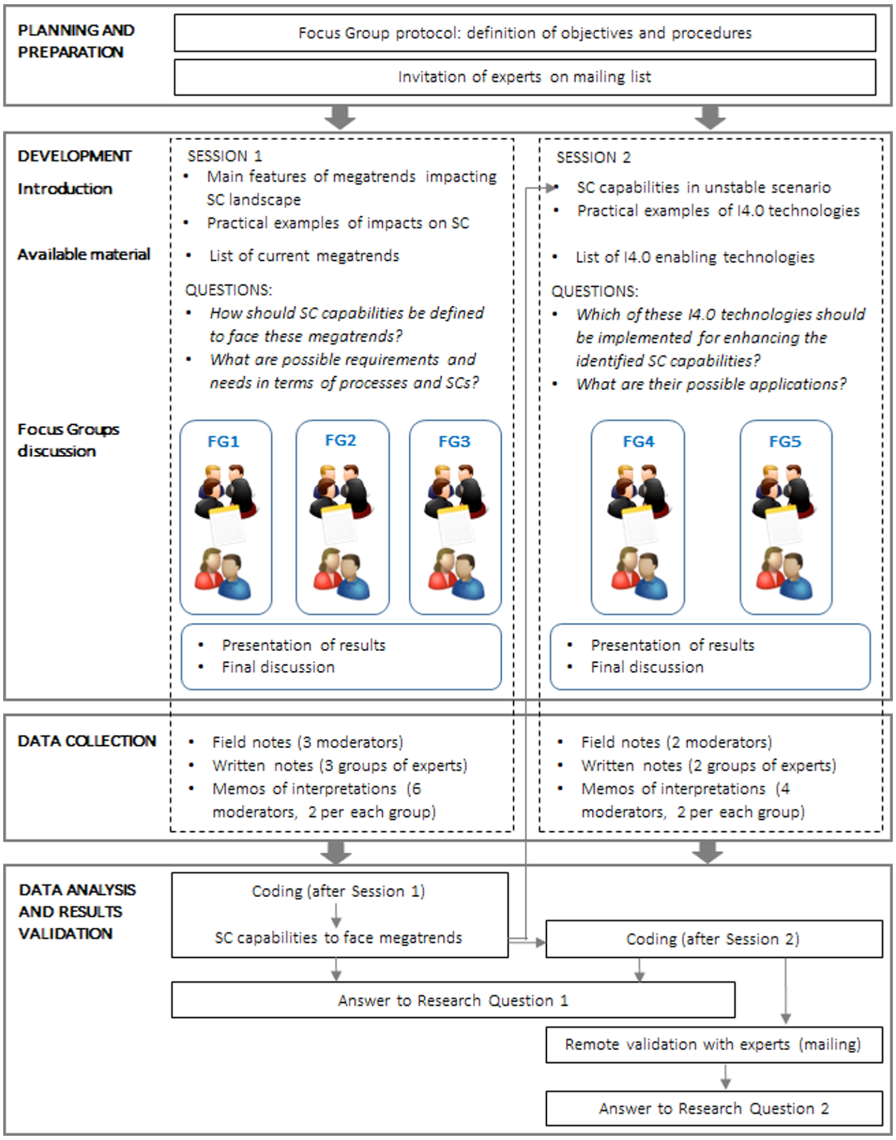


FIGURE 2 Focus group design.

participants also had the list of megatrends shaping the current supply chain landscape (as in Table 1) at their disposal. In the second session, the list of I4.0 technologies was also included as supporting material for both groups (as in Table 2). At the end of the discussions, a representative of each group was asked to synthetize the insights and present them to the other groups of the session, in an interactive environment. The final interactive gathering allowed further insights into the topics under investigation.

Data analysis

After the conclusion of both sessions, the two moderators of each group (one researcher and one independent practitioner) summed up the results of the interviews, including data collected from the participants' written notes and the researcher's field notes. Memos of interpretations of group interactions (Murfield & Esper, 2016) were also written down, highlighting the first emerging concepts around possible supply chain capabilities and enabling technologies that reached high levels of consensus, contextualized within the response patterns (Onwuegbuzie et al., 2009). This produced a total of five extensive reports, one per focus group, to be combined for coding and analysis by the research team. Indeed, analysis of multiple focus groups is useful to assess the meaningfulness of the themes that emerged in different groups and test them (Onwuegbuzie et al., 2009).

The data analysis phase took place after both data-collection sessions and consisted of two coding cycles. Following the Gioia methodology (Gioia et al., 2012), each researcher independently formulated codes for data collected in related focus groups, following an interpretive approach. In the first step, first-order concepts were

TABLE 3 Demographics of the three focus group participants in Session 1.

Group	Organization type	Role in organization	Years of experience	Company industry/area of expertise
1	Company	Supply chain manager	20–25	Automotive
	University	Senior researcher	10–15	Innovation and technology management
	Company	Purchasing manager	5–10	Production of industrial machineries and equipment
	Service and technology provider	Consultant	5–10	Business information systems
	Company	Head of customs	>25	Transport and logistics
	University	Researcher	5–10	Supply chain risk management
	University	Associate professor	15–20	Sustainability
2	University	Full professor	20–25	Supply chain strategy
	Consultancy	Project manager	5–10	Projects in pharmaceutical industry
	Company	Commercial director	>25	Fashion
	Company	Customer relationship responsible manager	10–15	Production of industrial machineries and equipment
	Service and technology provider	Senior consultant	10–15	Systems for energy and water efficiency
	Service and technology provider	Consultant	5–10	Business information systems
	University	Senior researcher	5–10	Crisis management
3	Company	Logistics manager	>25	Food and beverage wholesale
	University	Associate professor	15–20	Supply chain strategy
	Company	Commercial director	>25	Consumer goods
	Company	Customer relationship manager	10–15	Transport and logistics
	Consultancy	Project manager	10–15	Projects in retail and consumer goods
	Service and technology provider	Senior consultant	10–15	Identification and traceability systems
	Service and technology provider	Developer	5–10	Advanced analytics

identified among experts' quotations and written notes (1) per each megatrend (see Appendix 1) and (2) per each supply chain capability (see Appendix 2). The second step of the analysis was focused on transforming the initial concepts and quotations into second-order themes. After the first focus group session, the research team aimed to offer a more gestalt narrative of supply chain requirements to face each megatrend and related challenges. Thus, the last analysis step involved the abstraction into aggregate dimensions that described the supply chain capabilities to face the prevalent megatrends (final column in Tables A1–A6). This step resulted in the identification of five principal supply chain capabilities.

After the second focus group session, the second-order themes were developed to reflect the emerging applications of the I4.0 technologies per each supply chain capability (second column in Tables A7–A11). To compare and confirm emerging themes, multiple sources for testing and validation included (1) contributions in previous literature on supply chain capabilities and analyzing supply chains dealing with external turbulent conditions, (2) a round of discussion between the researchers after coding until reaching an agreement, and (3) remote validation and cross-checking of the resulting codes by expert participants, reached by email. In the final step of the analysis, the emerging aggregate dimensions, confirming or slightly reviewing the "whats" and "hows" of the possible applications of I4.0 technologies for enabling the five capabilities, described the extent of each technology application.

TABLE 4 Demographics of the two focus group participants in Session 2.

Group	Organization type	Role in organization	Years of experience	Company industry/area of expertise
1	Technology provider	General manager	20–25	Supply chain optimization and modeling solutions
	University	Researcher	10–15	Cloud platforms
	Technology provider	Private and public partnership manager	>25	Internet of things, security technologies
	Company	Logistics manager	>25	Automotive
	Company association	General manager	5–10	Sustainable urban development
	University	Associate professor	10–15	AI-based solutions for manufacturing
2	Competence center	Head	5–10	Digital supply chain
	Company	Operations manager	15–20	Power electronics
	Company	General manager	10–15	Consumer goods
	University	Senior researcher	5–10	Collaborative robotics
	Service provider	Project manager	15–20	3D printing

Research quality criteria

Quality criteria considered in the study were construct validity, internal and external validity, and reliability. Construct validity was controlled by mixing multiple experts with different backgrounds and roles (i.e., scholars and practitioners) in each focus group. Moreover, the researchers participating as moderators established chains of evidence while collecting the data during the five focus group discussions, also including feedback from key expert participants. The study could be limited in its external validity beyond the setting of part of megatrends characterizing the current environment. Still, it involved a relevant sample of people with expertise in supply chain management, related issues in changing and turbulent conditions, and I4.0 technologies. For internal validity, the researchers looked for consistency, compared and matched the findings of each focus group with the emerging findings of the overall session, and used multiple recording sources. Reliability was controlled by having skilled moderators (one researcher and one practitioner) and a research protocol guiding the study. Consensus sessions were conducted among researchers after completing the coding cycles, and results were shared with and cross-checked by participants to solve eventual issues or disagreements.

RESULTS

This section presents the insights gained during the two focus group sessions and after their analysis to answer the two research questions. Five possible supply chain capabilities (below described) emerged as most relevant to face current megatrends. For aging population, the human-centered supply chain capability was identified as the prevalent one. The growing urbanization resulted in the need to develop either an urban-centered or a customer-driven supply chain capability. Conversely, a fast reactive supply chain emerged as a key capability to align with challenges due to geopolitical shifts. The megatrends entailing the depletion of natural resources and the climate change resulted in the identification of a resource-efficient supply chain. Finally, other requirements to properly face climate change were referred to as a fast reactive supply chain.

Prevalent supply chain capabilities to align with megatrends and related challenges

This section describes the five supply chain capabilities identified by experts (Appendix 1) as the prevalent and most fitting ones with the features of the megatrends presented, thus answering RQ1.

Human-centered supply chain

Aging population, especially in developed countries, is already having a severe impact on the search for highly skilled workers. Experts agreed on the need to develop lifelong learning paths, especially for senior workers and through new training methods to enhance workers' digital skills and ensure the adoption of new technologies across the whole supply chain processes. A human-centered supply chain capability, enhancing and valorizing the role of human resources employed, would also support logistics operators in managing their tasks healthily and safely by adopting more ergonomic approaches and solutions. This also implies the need to adequately address workers' satisfaction and "actively promote their safety avoiding heavy and repetitive tasks." It also revealed the importance of increased social responsibility across the supply chain, adopting responsible business practices to contribute tangibly to the well-being of workers and society.

Urban-centered supply chain

With urban areas increasingly expanding and becoming more congested, supply chains should be properly configured to address the needs of final customers and citizens in urban-scale networks. Conversely, developing a supply chain capability focused on urban trends requires paying more attention to air pollution in highly populated cities—all in an effort to improve transportation in urban areas. Some participants suggested that companies move from larger facilities to smaller spaces inside cities to decrease production distance from the final market. At the same time, it would be necessary to implement last-mile transportation and just-in-time distribution of materials and components efficiently by realizing a network that integrates connected distribution centers and adapted logistics for smart cities.

In addition, the growth in the design and production of solutions within small factories and FabLabs leads to the integration of different flows (assets, people, vehicles, etc.) in the complex city logistics systems. Thus, the connection of the small factories with other facilities in smart cities could represent a key enabler of small-scale production of high-value, design-oriented, complex, and specialized goods. To this aim, supply chain actors should promote modularity in the supply and production network. With the increase in expectations of personalized interactions, as highlighted by the manager of a logistics company, "It is necessary to establish smart factories and connections with the local networks in short time, in the countries or regions where the products and services are requested and make the newly installed production capacity sustainable in a short horizon." Supply chains are thus required to improve the connection to urban (local) points. This could be possible if global or local sourcing is supported by a local distribution, properly integrating facilities and systems.

Customer-driven supply chain

Trends as the shifts in consumer demand require a rethink of customer relationships and an increased ability to understand, detect, and answer customer needs. As highlighted by experts, customers are indeed "increasingly challenging companies to meet their expectations and offer even higher service levels." Moreover, uncertainty and volatility in customer demand imply difficulty forecasting and planning the overall supply chain. Actors thus need to adopt intelligent tools and solutions with much higher levels of intelligence in gathering market information. Customers wish to express their own singularity through even more personalized solutions and a novel dedicated shopping experience and delivery. According to experts, it is thus necessary "to enhance the capacities for matching the customers' needs in terms of customization of the product and related services." To improve the relationship with the customer, it is also necessary to decrease the distance with the final market to provide retailers and consumers with an enhanced last-mile delivery experience. Practitioners also underlined the importance of a flexible management of the network and production thanks to "real-time integration through seamless data exchange along the whole supply chain, together with advanced production technologies." Moreover, due to the rise of personalization and the DIY paradigm, experts reported the consequent emerging need to support customers in designing, making, or assembling products.

Fast reactive supply chain

The trend entailing fragmented regulatory frameworks and protectionism may affect trade restrictions and segment markets on a national basis. These changes create potential turbulence for supply chains with consequences on sourcing decisions, logistics and manufacturing operations, and risk management. As mentioned by experts, these trends can lead to difficulties in configuring global networks, with the need to increase the capability to quickly redefine the feasible options for sourcing raw material and components. Multiple source options also need to be considered to reduce the risk of trade barriers in some countries. Important supply chain practices are related to fitting strategies for mitigation, prevention, and recovery from emergency, and resilience strategies to prevent negative impacts, establishing reliable distribution systems where transparency and traceability can help recognize disruptive events.

Experts reported that trade restrictions can lead to severe problems in the upstream supply chain for sourcing materials and in the downstream network for entering existing and new markets. For this reason, it is necessary to work on methods for the reconfigurability of supply chains. Moreover, it revealed the need to reinforce and create local networks to overcome differences in regulatory frameworks that can cause global sourcing problems.

As underlined in the discussion, it is crucial to establish strategic points in the supply chain to be prepared and easily react to instability caused by disruptive events such as natural disasters and social crises.

Resource-efficient supply chain

Several participants from the focus groups agreed that the depletion of natural resources would change the approaches toward efficient use of resources at the company and supply chain level. An expert mentioned that sustainable solutions "should not increase prices or decrease flexibility, rather enhancing the cooperation along the network to optimize resources use," thus fostering the use of "secondary raw materials also in the development of new products." The discussion also highlighted that implementing allocation approaches can help efficiently employ resources. The supply chains may consider investments in monitoring scarce resources to foster minimal consumption and encourage recovery initiatives to achieve higher sustainability targets. A devoted area of concern is the waste produced along the supply chain, with new waste management practices and recycling strategies to be implemented in the whole network to make processes more efficient.

A supply chain capability aimed at better exploiting resources with less pollution emerged in the fundamental coping with climate change issues. An expert reported that, in the supply chain of the fashion sector, "We are studying new ways to adopt substitute and sustainable materials to avoid pollution both during production, usage and dismissal." In this sense, there was substantial agreement on the need to carry out supply-level strategies to reduce operations' ecological footprint, e.g., by modernizing freight transportation or investing in on-polluting energy sources.

I4.0 enabling technologies to support supply chain capabilities

This section describes the technologies supporting the five supply chain capabilities and their applications resulting from the analysis (Appendix 2) to answer RQ2.

Technologies for human-centered supply chain

The discussion in the second focus group revealed that a human-centered supply chain capability should encourage the adoption of technologies supporting the development of new skills and lifelong learning. New training methods implementing augmented reality and immersive virtual environments could "increase in all kinds of workers the capability of using new technologies to work more efficiently." Indeed, visual computing can be essentially adopted to improve professional skills and help operators on complex tasks in the assembly and logistics phases. Moreover, as suggested by a technology provider, virtual environments integrating BDA enable one to customize training content by adding real-world information. A knowledge-management platform has further potential for on-the-job training purposes and delivering e-learning content to workers involved in different supply chain processes.

Technologies for a human-centered working place in logistics and manufacturing typically include IoT and smart wearable devices. Experts discussed their implementation to monitor working parameters to improve the safety and ergonomics of the operators as well as their productivity in shop-floors and warehouses. Particular attention should further be given to privacy issues when implementing these technologies. In addition, collaborative robots (i.e., cobots) have already been adopted in some factories, warehouses, and distribution centers to relieve human workers from dangerous and heavy tasks. Still, according to an expert from the robotic sector, they "need to be further improved in terms of new control motion systems and sensors enhancing visual and gestural movements for more accurate interaction with workers." Advancements are also elicited in discussions concerning the use of exoskeletons to help workers, thus enhancing safety and productivity in production and logistics.

Technologies for urban-centered supply chain

The urban-centered capability emerged to be supported by two main usages of digital technologies. Urban manufacturing was the first application area analyzed from the focus group results, with smaller plants located in urban areas and closer to final consumers. A service and technology provider representative highlighted that 3D-printing boosts production of personalized products and components close to the customer and enables them to quickly adapt to its specifications, until ideally "reaching the so-called lot one production that enhances the mass customization at low cost." Moreover, small- and medium-scale plants provided with AM solutions can act as service centers to directly support the final customer in the production or assembly stage of the specific and personalized product. In addition, the implementation of cloud-based computer systems connecting supply chain actors could facilitate flexible management and centralized sourcing for multiple DIY manufacturers both for B2B and B2C contexts.

Experts also highlighted the need for new solutions for sustainable sourcing and distribution in urban areas. They should address mobility in cities and contribute to solving problems of traffic and air pollution. New models such as light electric vehicles, for example, could be widely used for supply chain logistics; however, they have to be equipped with location technologies such as GPS tracking systems and full integration of well-developed communication infrastructure. There is "the need to regulate 5G to solve interoperability problems and ensure basic data access, connecting fast (and in a reliable way) the whole supply chain." The connection to urban points by properly linking operations and logistics (especially transportation) at the local level and with global supply can be enhanced thanks to a proper integration of communication technologies and the data available from location technologies. Their application, associated with IoT, can indeed make the transport of goods and the communication along the overall chain more efficient, "with real time data and dynamic availability (and versatility) of data." With the multiplication and intensification of the different flows into more populated urban spaces, practitioners highlighted the importance of optimizing last-mile delivery, which can be performed with autonomous transport systems such as vehicles and drones and by sharing transportation models for more sustainable personalized shipments.

Technologies for customer-driven supply chain

The increased application of digital technologies, especially in the downstream network, would improve customer-driven supply chain capabilities. Experts highlighted that research should address new ways to connect with consumers by adopting technologies to detect and analyze customer and market needs and transform them into even more personalized products. BDA was revealed to be useful to support the analysis of demand variability and investigation of shopping behaviors, "extracting meaningful, relevant information from the amount of available data." AI and smart wearable devices integrated with BDA were also argued to be essential for gathering and handling massive data from social media and consumer habits. They would allow one to create customer profiles and detect new market trends, possibly predicting the high-demand variability while increasing customer engagement and satisfaction. Thus, an increasing ability to learn customer preferences, habits, and values would facilitate the supply chain tailoring.

Moreover, practitioners highlighted how cloud-based computer systems associated with social sensors could be essential in developing new customer data platforms relying on first-hand data, thus creating a persistent customer base for customized products. According to experts, these systems could enable the creation of "co-creative prosumer B2C and C2C platforms connecting consumers, professionals, and engineers in a seamless and frictionless customer journey." Finally, the integration of additive and hybrid manufacturing is already bringing new supply chain opportunities for the realization of customized products and components, thus lowering manufacturing costs and improving product performance. The importance of technologies for secure and trusted customer relationships was also highlighted. Distributed ledger and blockchain revealed their support in handling multiple decision levels and improving the relationship between final customers and companies by ensuring that transferred data are original, and to conceive smart contracts for regulating different processes – from design to production to logistics.

Technologies for fast reactive supply chain

Aiming to be ready to change configurations quickly and to enact resilience, experts underlined the need to optimize (information and products) flows along with the network for fast reconfiguration when facing unexpected events. Appropriate data management systems and BDA were argued to support this process in terms of data collection from multiple sources along the supply chains (i.e., machines, humans, factories, trucks) as a basis for forecasting changes in demand and the supply side and to react to fast changes. Moreover, supply chains need to be able to handle data upon which to design predictive models based on AI to support risk management and to define contingency plans in the presence of catastrophic events and geopolitical shifts.

IoT (associated with BDA), communication infrastructure, and location technologies were revealed to be helpful in detecting real-time disruptions (and facilitating sharing of information) along with the network. They have key potentialities in supporting the optimization of logistics and manufacturing operations flow based on tracing and tracking of items. The extension of the concepts of multi-actor digital platforms to support the interaction of supply chains with different stakeholders (i.e., companies, NGOs, government, and citizens) can help handle flows along the network based on real-time data. They can contemporarily support a multiple source strategy and the reconfiguration of networks upon disruptions by sharing information across processes and multiple kinds of actors.

Technologies for resource-efficient supply chain

Different technologies can support efficient exploitation of resources in supply chains. The optimization of supply chain operations, especially production, was the main application area emerging from the participants' discussion. Specifically, with AM, it is possible to realize lot-one products only when they are needed, avoiding stocks, as reported by an expert from automotive sector: "In our supply chain, we are testing AM to produce ad hoc single spare parts of equipment without the use of the related moulds usually necessary in conventional manufacturing processes, avoiding transportation of components from suppliers to manufacturers." In addition, the relevance of cloud-based computer systems emerged to support the management of shared resources and operations along the supply chain. They should be exploited to enable real-time information sharing on procurements and consumption of raw materials and components among different plants and actors, with also-shared scheduling of production, distribution, and services.

Another group discussion result highlighted that increased resource efficiency is strictly related to monitoring and controlling energy usage and waste along with the supply chain processes. To this aim, the synergic application of BDA and AI is currently under development in different sectors (for example, steel) under the industrial symbiosis approach. In addition, IoT allows for systematic data collection from various actors on procurement and consumption of energy and materials and signals possible excess inventory or wastes.

Supply chain capabilities fitting with megatrends and I4.0-enabling technologies

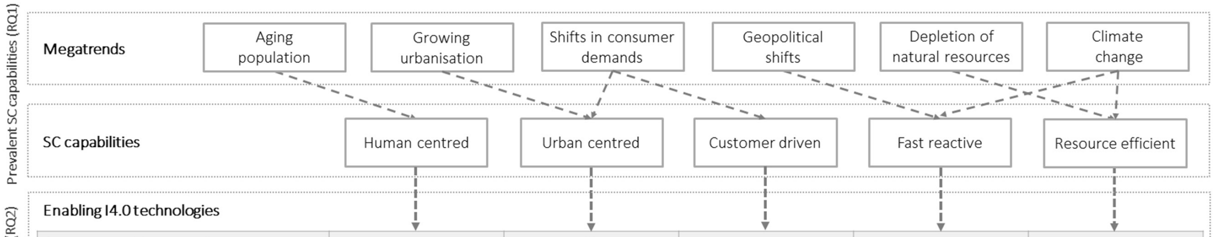
Table 5 summarizes the results from the analysis, i.e., the aggregate dimensions identified in Tables A1–A6, in terms of supply chain capabilities mostly fitting the current megatrends and related challenges, and in Tables A7–A11, in terms of technologies and their applications enabling the specific supply chain capabilities.

DISCUSSION

Findings from the focus groups show that nowadays managers should rethink supply chains to empower different capabilities fitting the multiple trends, thanks to ad hoc pools of I4.0 technologies. The framework that can be derived from this work (Figure 3) summarizes the link between the different dimensions we have been studying throughout this work: aging population; growing urbanization; shifts in consumer demands; geopolitical shifts;

TABLE 5 Supply chain capabilities and I4.0 technologies supporting them in facing current megatrends.

Megatrends	Supply chain capabilities	Extent of I4.0 technologies application	I4.0 enabling technologies
Aging population	Human-centered supply chain	Technologies to support development of new skills and lifelong learning	BDA, cloud-based computer systems, visual computing
		Technologies for a human-centered working place in logistics and manufacturing	Robots, IoT, mobile, and wearable devices
Growing urbanization, shifts in consumer demands	Urban-centered supply chain	Technologies for urban manufacturing	Cloud-based computer systems, AM
		Technologies for sustainable sourcing and distribution in urban areas	Autonomous transport systems, communication infrastructure, identification, and location technologies
Shifts in consumer demands	Customer-driven supply chain	Technologies to detect and analyze customer and market needs and transform them into (personalized) products	AI, cloud-based computer systems, IoT, BDA, mobile and wearable devices, AM
		Technologies for secure and trusted customer relationships	Distributed ledger/blockchain
Geopolitical shifts, climate change	Fast reactive supply chain	Technologies for prompt reconfiguration of supply chain	AI, IoT, BDA, Identification, and Location Technologies
		Technologies for sharing information across processes and across actors	AI, IoT, BDA
		Technologies for risk management	AI, communication infrastructure
Depletion of natural resources, climate change	Resource-efficient supply chain	Technologies for optimization of supply chain operations	Cloud-based computer systems, AM
		Technologies for monitoring and control of energy usage and waste	AI, IoT, BDA



Enabling I4.0 technologies	Human centred	Urban centred	Customer driven	Fast reactive	Resource efficient
Autonomous Transport Systems		X			
Robots	X				
Artificial Intelligence			X	X	X
Cloud-Based Computer Systems	X	X	X		X
Internet of Things	X		X	X	X
Distributed Ledger/Blockchain			X		
Big Data Analytics	X		X	X	X
Mobile and Wearable Devices	X		X		
Communication Infrastructure		X		X	
Identification and Location Technologies		X		X	
Visual Computing	X				
Additive Manufacturing		X	X		X

FIGURE 3 Resulting framework linking megatrends, supply chain capabilities, and I4.0 enabling technologies.

depletion of natural resources and climate change; prevalent and most fitting supply chain capabilities to changing trends; and the I4.0 technologies enabling the identified supply chain capabilities, considering the promising role of technology among traditional contingency factors (Victer, 2020).

The contingency perspective was adopted in the definition of capabilities (Victer, 2020) since it is demonstrated to be particularly useful for identifying requirements pertinent to the proper configuration of supply chains (Burton & Obel, 2004). It rejects one best way to organize a system, suggesting to determine different alternatives according to the context trends and related challenges (Donaldson, 2001). Contingencies are defined as outside events that affect organizations and supply chains over which they do not have direct control (Sousa & Voss, 2008).

Focus groups' results highlighted how possible contingencies, in terms of megatrends and related challenges affecting the current and future supply chain landscape, require companies to develop and align their capabilities at the supply chain level to these external changes and how technology investment decisions can help to face them properly.

Specifically, five prevalent supply chain capabilities have been identified to answer RQ1 as a way to match the challenges of the different trends. In particular, the human-centered supply chain capability helps to face challenges derived from aging populations and the need of training and lifelong learning. The urban-centered supply chain capability support to face the growing urbanization and need of avoiding congestion of people and information flows along the same urban paths. The customer-driven supply chain capability help to face shifts in consumer demands and increase of individualism. The fast reactive supply chain enables one to face changes in geopolitical trends and intensification of natural disaster. Finally, the resource-efficient supply chain capability is linked to the depletion of resources (like water and raw materials) and climate change-related disasters.

Answering to RQ2, I4.0 technologies to empower supply chains in facing megatrends were identified, and their specific applications for each of the supply chain capabilities were depicted. The potential offered by I4.0 technologies in supporting the five supply chain capabilities can be explored by companies, and specific applications have been identified. In particular, it emerged that some technologies are applicable to support many different supply chain capabilities in a multitask perspective and can be instantiated specifically for facing related challenges. For example, AI importance has increased in the last years, and several different applications are proposed by experts and in the literature. With specific models of AI-like machine-learning models and expert systems, it is possible to facilitate the resource-efficient supply chain capability by supporting real-time analysis of data on energy consumption and CO_2 emission throughout the whole supply chain and support the optimization of manufacturing processes for energy saving and emission reduction (Zuo et al., 2018). In applying AI for a fast reactive supply chain capability, the focus is on risk management, with rapid and adaptive decision-making tools, based on potentially large and multidimensional data sources, for the identification, assessment, and monitoring of unexpected events or conditions that have an impact, mostly adverse, on any part of the supply chain (Baryannis et al., 2019), which helps in the reconfiguration of the entire network, especially in the case of natural disasters or political instability in supplier countries. A customer-driven supply chain capability can benefit from AI systems when it is conceived for demand forecasting and customer requirements formalization to face changing customer demand and increased individualism and the need for product personalization.

For what concerns BDA, the experts highlighted potential benefits for the resource-efficient capability, also confirmed in Katchasuwanmanee et al. (2016), proposing to gather big data from internal and external processes of the supply chain in a smart system able to improve production efficiency and reduce CO_2 emissions. BDA applications are also necessary for a customer-driven supply chain capability to support the detection of customers' needs and changes in market demand (Kache & Seuring, 2017), aiming to offer personalized products/services (Erevelles et al., 2016; Tiwari et al., 2018). Detection of external factors affecting supply chains and minimizing the negative impact of different network risks is necessary for the fast reactive capability (Gunasekaran et al., 2015) by implementing proactive supply chain management strategies when there are incoming economic trade barriers. Thus, BDA can enhance resource-dependence models to synchronize the delivery of services for humanitarian reasons by aligning recipient community needs with resources from various stakeholders along with the network (Prasad et al., 2018). Moreover, BDA can be the basis for improving visibility in a humanitarian supply chain and coordination among actors in the case of swift trust (Dubey et al., 2018; Sharma & Joshi, 2019). Finally, in the case of human-centered supply chain capability, BDA can support process mining to elaborate the data coming from virtual reality to obtain improved assembly models for enhancing the training of the workers (Roldán et al., 2019).

Also, the literature and experts have recognized IoT as the main I4.0-enabling technology to play a key role in supporting the majority of the identified supply chain capabilities. In particular, sensors embedded along reverse logistics processes can help cloud-based waste monitoring for efficient resource capability (Garrido-Hidalgo et al., 2019), thus enabling real-time and dynamic collection of data for green inventory management (Chen, 2015) to avoid depletion of resources.

Moreover, IoT can be used for enhancing customer-driven supply chain capability to support the collection of information on changing customer habits and preferences, with social sensors composed of integrated hardware (smart devices) and software (apps) configured with unique resource identifiers on Internet (Ding & Jiang, 2016). In the case of the human-centered supply chain capability, the discussion with experts underlined the importance of leveraging the integration of IoT with wearable technologies as a synergic application with augmented reality and cloud storage. This supports collaboration and interconnections among smart objects and operators' activities with a specific human interface that increases safety (Abdel-Basset et al., 2018), in particular, to face lifelong learning needs and support training on logistics operations.

During the discussion, cloud-based computer systems were revealed to play an essential role in the development of multiple supply chain capabilities, thus enabling information sharing among partners for utilization of manufacturing resources (Xu et al., 2018) and real-time life-cycle information (Simeone et al., 2018; Xing et al., 2016) in resource-efficient capability and for exchanging e-learning material in human-centered capability. Cloud-based platforms could also be successfully adopted to enhance urban manufacturing supply chain and customer-driven supply chain capabilities. The joint management of highly personalized solutions indeed requires easy sharing and rapid organization of multiple types of market and operational information, thus exploiting the distributed technological structures (in local areas) that support interoperability and remote access (Ardito et al., 2018). A cloud-based computing system has not emerged for fast reactive supply chain capability since it is necessary to implement communication infrastructure and several different actors that need to be connected first at the local level with sensors and IoT.

Some technologies appeared to support only specific supply chain capabilities and related processes, as it is clear that they are currently used and exploited mainly at the company level. Conversely, their adoption to support processes along supply chains seems not yet perceived by experts as a priority despite their potential and interest expressed in the focus groups. In particular, experts envisaged a key role to be further developed and studied for autonomous vehicles that enhance the urban-centered supply chain capability. Using drones for a point-to-point personalized delivery, thanks to appropriate simulation tools that replicate the kinematics of urban logistics, can enable the integration of last-mile logistics operations within smart cities (Bechtsis et al., 2018). Robots, specifically cobots, were cited by experts as the main facilitators only for a human-centered supply chain capability. The human interaction issue is particularly relevant to answer to the challenges of aging workforce in operations and logistics tasks. Human–robot cooperation would help avoid human musculoskeletal disorders and other physiological stress (Bogataj et al., 2019).

Distributed ledger technologies can enable the customer-driven supply chain capability by increasing visibility and security of transactions and information flows across the supply chain, together with efficiency based on record-keeping. Visual computing technologies enable augmented and virtual reality environments. They have been considered valuable mainly for human-centered supply chain capabilities to support training for industrial operators, especially in assembly tasks, which take advantage of an immersive interface to learn and perform new tasks (Roldán et al., 2019).

Other technologies like wearable devices have viability for the supply chain to enhance customer-driven and human-centered capabilities, thus helping to posture detection and body motion, track customers' and workers' activities, and collect data in the background to promote ergonomics and safety in the work environment. Communication infrastructures may be the potential backbone for urban-centered and fast-reactive supply chain capabilities. At the same time, additive manufacturing supports customer-driven capability, offering the possibility to personalize products also in the urban context. This analysis helps show the instantiation of each technology in the supply chain capabilities according to specific needs. The overall framework is useful to make companies understand where and how it is necessary to intervene to improve supply chain capabilities in terms of processes to face external contingencies.

CONCLUSIONS

This paper aims to gain a deeper understanding of which supply chain capabilities shall be implemented and how I4.0 technologies can be adopted along the whole supply chain to enable companies to cope with the turbulent and changing nature of megatrends as from the literature. Given these external factors of change, we analyzed theories on implementing organizational and supply chain capabilities that emerged to match and fit with requirements from megatrends. Existing frameworks on the role of technologies have been investigated. Different applications emerging from experts and also present in the literature were discussed to explore a pool of choices, their possible effects, and issues on specific I4.0 technologies still requiring research contributions.

According to the contingency view, this allowed proposing our own framework upon which we built a comprehensive investigation of supply chain capabilities needed to face such megatrends. Consequently, the supply chain requirements and the applications of the I4.0 paradigm emerging in focus groups guided the identification of five specific supply chain capabilities and the I4.0 technologies to enable them to face megatrends. We integrate the different components (megatrends, capabilities, and technologies) to contribute to the academic and industrial debate on the evolution of supply chain management (Melnyk et al., 2017).

The systemic approach of this work facilitates the theoretical contribution and allows us to outline a path to I4.0 that relies on the potential of the complete pool of technologies at the supply chain level. Their full integration indeed assures the most significant effect of these technologies among factories and with supply chain actors fully aligned. Following the call to focus on specific contextual (or contingency) variables for developing supply chain responses (von Falkenhausen et al., 2019), we depicted how supply chains can face changing and turbulent megatrends with different approaches to exploit the potential of I4.0 technologies, assuring that the technologies to be adopted are targeted to enable specific supply chain capabilities.

Moreover, this work attempts to bridge the gap of previous studies that have sought to take a comprehensive view of supply chain facing megatrends and to examine the interplay between them and supply chain capabilities using the contingency approach (e.g., Prajogo et al., 2018; Simangunsong et al., 2012) and studying how I4.0 can be instantiated for each specific capability. Results can be considered as a reference for prevalent supply chain capabilities with contextual variables encompassing a single company or sector (von Falkenhausen et al., 2019).

Our contribution is mainly related to matching supply chain capabilities with contingency overcoming the classic perspective based on internal factors like demand variability, product variability, and customer demand but enlarging to external factors influencing supply chains. Moreover, considering the state of the art of I4.0, we made an effort to go beyond company borders and to consider related technologies as enablers of interconnections not only between machines but also between companies.

In terms of managerial implications, the work provides supply chain managers with an overview of how megatrends can be faced in their supply chain and alternative choices to be adopted to manage specific aspects. Decision-makers should consider the relevance of the contingent conditions (i.e., aging population, growing urbanization, shifts in consumer demands, geopolitical shift, depletion of natural resources, climate change) and derived supply chain requirements to rethink their processes accordingly. The resulting framework can be used in the definition of capabilities and mapping, which are the proper supporting I4.0 technologies for maintaining a high level of supply chain competitiveness. The paper contributes toward understanding which are the different instantiations of I4.0 technologies and can increase awareness of their potential at all decisional levels, both for managers and operators of supply chains.

Companies can consequently use this to plan actions that will foster the appropriate I4.0 applications among the different roles of the supply chain and to address investments according to specific megatrends and the required supply chain capability. Finally, the main limitations of this work are related to the use of qualitative methodology and the restricted number of megatrends considered. A similar study can be helpful in considering megatrends like the increase of fintech, the role of cryptocurrencies, and health pandemics that could further affect supply chain processes. Additional research is also needed to rank sources of turbulence for supply chains, prioritizing the most effective supply chain capabilities to place them beyond the limitations of cost-efficiency drivers.

Moreover, further empirical research in this area would help to assess and validate the proposed framework and test the relationship between the constructs of supply chain capabilities and the effect of I4.0 technologies adoption on supply chain performance as well as instantiate the findings to the need of specific sectors of the manufacturing industry. This may include conducting an in-depth study of a combination of the five supply chain capabilities and a bundle of adopted technologies or a survey of a comprehensive sample of companies and supply chains. The organization of focus groups with companies from the same sector would also enhance the understanding of more specific patterns characterizing a single industry.

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ORCID

Elena Pessot https://orcid.org/0000-0002-0072-8881

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AUTHOR BIOGRAPHIES

Elena Pessot is Assistant Professor in Management Engineering at the University of Siena. She holds a PhD in Industrial and Information Engineering from the University of Udine and was a Senior Research Fellow at the National Research Council of Italy. Her research interests are in the areas of digital transformation and Industry 4.0, open and social innovation, complexity management.

Andrea Zangiacomi is researcher at CNR-STIIMA, he has a degree in Industrial Engineering and his research interests are related to Supply Chain Management and Digitalization. These topics have been explored in various EU-funded projects. He has been involved in roadmapping activities for the manufacturing sector. He also has a degree in Psychology of work and organizations. Interests in this field concern the impact of new technologies and interaction design.

Irene Marchiori graduated in management engineering at the University of Padova. She has worked at CNR as research fellow. Her areas of expertise are Supply Chain Management and operations management with application to fashion sector. She where she was involved in national and EU projects where she was involved also to support project management. She is currently product manager in manufacturing company.

Rosanna Fornasiero is director of research at CNR (National Council of Research-Italy). Her research areas are Supply Chain Management, operations management, and technology roadmapping. She has experience as project coordinator and principal investigator of several European projects in H2020 and Horizon Europe. She is coordinator of the Roadmapping group of the National Cluster of Intelligent Factories. She collaborates with the University of Padua as contract professor.

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APPENDIX 1

CODING SUPPLY CHAIN CAPABILITIES FOR ALIGNMENT WITH MEGATRENDS CHANGING SUPPLY CHAIN LANDSCAPE

TABLE A1 Coding supply chain capabilities for aging population.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• "Our older workers lag behind the fast development of technologies." • "In the logistic sector, we believe it is necessary to ensure lifelong learning paths and adopt new technologies." • "It is necessary to develop new training methods through modular approaches to enhance workers' digital skills, both blue and white collars, junior and senior." • "In our company we are struggling to find workers with the right competencies to handle digital solutions"	Need of new digital skills and lifelong learning	Human-centered supply chain
• Workers' well-being • "We should leverage digitalization not only to gain economically and environmentally but use it for social responsibility across supply chains." • The social aspect of supply chain	Increase social responsibility	
• "We would also support operators in the shop floor, for managing their tasks in a healthy and safe manner through the adoption of more ergonomic approaches" • Improvement of working conditions • "In the logistic sector, we could improve satisfaction and safety of our workers avoiding heavy and repetitive tasks for operators." • "In our warehouses, we need to prevent the risk of injuries from lifting, pushing, and pulling heavy loads"	Need for more ergonomic solutions in logistics tasks	
• "We need to face some outbound logistic challenges such as optimizing last-mile delivery and implementing order status real-time visibility" • "In our company, it is necessary to train warehouse operators to optimize order picking accuracy and safety." • "Logistic workers must have the skills required to implement defined procedures and to operate specific machinery"	Training focused on logistics operations	

TABLE A2 Coding supply chain capabilities for growing urbanization.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• More attention to air pollution in urban areas with a growing population • "The expansion of the urban space implies for companies that they will deal with more complex city logistics systems, and these will impact on different flows, including assets, people, vehicles ... and these have to be integrated in a harmonized and efficient manner (for example, to avoid the risk to run trucks half-empty)"	Improve transportation in urban areas	Urban-centered supply chain
• Supply chain configuration addressing the needs of both final customers and citizens of megacities • Companies moving from larger facilities to smaller spaces inside cities	Decrease distance of production from final market	
• Implement last-mile transportation and just-in-time distribution of materials and components • In smart cities need of a network that integrates connected distribution centers and adapted logistics • Need to consider the level of digitalization and infrastructure in cities	Interconnected logistics infrastructure in cities	

TABLE A3 Coding supply chain capabilities for shifts in consumer demands.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• Mix between local and global sourcing, with a higher percentage of local sourcing supported by a local distribution • Use of local resources with small factories located in cities • Optimization of logistic communication between connected small factories and FabLabs	Connection to urban (local) points	Urban-centered supply chain
• The small factories/FabLabs located nearby "may act also as service centres, to directly help customers to produce their own products ... to let them design or support them in the stage of production or assembly of her/his specific and personalized product" • With the increase in expectations of personalized interactions, "It is necessary to establish smart factories and connections with the local networks in short time, in the countries or regions where the products and services are requested, and make the newly installed production capacity sustainable in a short horizon" • Modular products for late customization • Production adapted to the changing urban consumer needs	Modularity of supply and production network	
• "Nowadays uncertainty/volatility in customer demand implies, as a consequence, difficulty in forecasting and planning in the overall supply chain" • "supply chain professionals need tools and solutions with much higher levels of intelligence in gathering information about markets" • Big data models	Capabilities to understand customer needs	Customer-driven supply chain
• "Customers (in fashion but also in B2B industries) are getting more and more used to high service levels, and are increasingly challenging companies to meet and overcome their expectations" • "Some companies in customer good industry look for new tools to facilitate one-of-a-kind customization" • "It is necessary to enhance the capacities for matching the customers' needs in terms of customization of the product and related services" • "Strengthening the last-mile storage and distribution system will enable to provide enhanced customer service"	Improve the relationship with the customer and decrease distance with market	
• Full transparency • "It is required real-time integration through seamless data exchange along with the whole supply chain, from customer to factory shop floor to suppliers, together with advanced production technologies to increase the capabilities of supply chain to be flexible and agile" • Interoperability through open data	Flexible management of the network and production	
• IPR of product design • "In the fashion sector we feel the need to be capable of defining customer-centric measures for value co-creation, overcoming traditional performance indicators" • Do-it-yourself paradigm	Help customers to produce their own products	

TABLE A4 Coding supply chain capabilities for geopolitical shifts.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• "It was happening a few years ago that we had a disruption with the provision of a material due to transportation strikes in the country of our only supplier" • "The complexity of our product takes us to search for many different suppliers to prevent problems in one specific node of the network"	Multiple source options	Fast reactive supply chain
• "When there is a disruption, it is difficult to have responsive partners at a global level" • "In case of global suppliers, it is not enough to control operational activities, it is necessary to know the country conditions from the political, economic and social point of view" • Challenging to overcome differences in regulatory frameworks between different countries	Identify new local partners	
• "It was happening a few years ago that we had a disruption with the provision of a material due to transportation strikes in the country of our only supplier" • "Lack of transparency and traceability in the global supply chain especially in developing countries, creating legislative enforcement issues in the non-EU countries that produce pharmaceutical commodities with problems, in particular when catastrophic events happen"	Reliable distribution system	
• "To quickly redefine the best option for sourcing of raw material and components, to reduce the risk of trade barriers in some countries" • "The increase in political issues related to trends such as fragmented regulatory frameworks and protectionism impacting on trade restrictions and segment markets" • "In the beverage sector, we had several problems with trade restrictions to consolidated markets, and there is the need to be capable of finding new markets and configure new commercial routes"	Reconfigurable supply chain	
• "In our company, we are rethinking resource management strategies implementing new features to handle redundant sources for materials and components" • "We plan stocks in strategic points of the supply chain"	Stocks in strategic points of the supply chain	

TABLE A5 Coding supply chain capabilities for depletion of natural resources.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• Implementation of resource allocation approaches in the supply chain • "There is the need to introduce sustainable solutions that should not increase prices or decrease flexibility, rather enhancing the cooperation along the network to optimize resources use" • Use of secondary raw materials also in the development of new products	Efficient use of resources along with supply chain levels	Resource-efficient supply chain
• Consumption of energy generated in manufacturing plants (e.g., in the form of stream or heat) for logistics needs and purposes • Standardized information for consumption monitoring and better decision-making for scarce resources	Monitoring of scarce resources (i.e., water, energy) consumption	
• New practices of waste management • New recycling strategies, extended to the whole network • New business models for waste sharing among stakeholders at the right moment	Waste management	

TABLE A6 Coding supply chain capabilities for climate change.

Representative quotes/concepts	Supply chain requirements	Supply chain capabilities
• "We are studying new ways to adopt substitute and sustainable materials to avoid pollution both during production, usage and dismissal" • "The usage of non-polluting energy sources is an area of investment that now needs to be covered at supply chain level, to properly ensure sustainability" • Resource scarcity to be faced with a circular economy approach	New approaches for sustainable production	Resource-efficient supply chain
• Modernizing mobility and freight transportation aimed at sustainability and reduction of carbon footprint • Design-for-environment strategy to minimize products' environmental footprint	Reduction of supply chain operations ecological footprint	
• Need of contingency plans • "We encountered few times problems of provision of materials due to flood and storm in the country of our only supplier in Asia" • Increase capability of risk management	Contingency plans	Fast reactive supply chain
• "It can be a cost, but we are planning to keep redundant resources and stocks in strategic points of the supply chain" • "The need to assure service to our customer is higher than the cost to keep other resources"	Redundant resources	

APPENDIX 2

CODING OF TECHNOLOGIES AND THEIR APPLICATIONS FOR SUPPLY CHAIN CAPABILITIES

TABLE A7 Coding of technologies and their applications enabling human-centered supply chain.

Representative quotes/concepts	Technology application	Extent of technology application
• "The development of new training methods could be based on innovative technologies, such as virtual and augmented reality to increase in all kinds of workers' capability to use new technologies to work more efficiently" • "Visual computing seems us to be essential to improve professional skills and help operators in complex tasks in the assembly and logistics phases" • "virtual environments in the Automotive sector can also be enriched through the application of data science techniques to customize training contents by real information"	Creation of virtual environments integrating BDA and visual computing for the training of workers	Technologies to support the development of new skills and lifelong learning
• E-Learning platforms to train logistics operators • "Digital platforms have a big potential for knowledge management purposes, training on-the-job, and delivering e-Learning content to our workers"	Knowledge management platforms for competence management and training	
• "Integration of IoT and wearable devices could support monitoring working parameters as a way to improve the safety and ergonomics of our operators both in shop floors and warehouses" • Wearables and connected-worker solutions for boosting worker productivity	To assure ergonomic and safe working place and increase productivity with IoT and Smart Wearable Devices	Technologies for a human-centered working place in logistics and manufacturing
• "Cobots need to be further improved in terms of new control motion systems and sensors: they have to enhance human-machine interfaces that are effectively based on visual and gestural movements for more accurate interaction with workers" • "Robots could help our workers and support them in tedious and heavy tasks, enhancing safety and productivity both in production and logistics"	Robots for relieving operators' workload	

TABLE A8 Coding of technologies and their applications enabling urban-centered supply chain.

Representative quotes/concepts	Technology application	Extent of technology application
• "Additive manufacturing enhances a flexible production nearly located to the market that appears fundamental to sustain the personalization trend" • 3D-printing boosts the production of personalized products and components until ideally "reaching the so-called lot-one production that enhances the mass customization at low cost" • Creation of modular systems (small, smart, adaptable, and efficient factories) to be connected with local networks for urban manufacturing	Additive manufacturing (3D printing) for small-scale production closer to final customer	Technologies for urban manufacturing
• Centralized sourcing for multiple manufacturers of small and highly personalized production in urban areas, both for B2B and B2C contexts • Common online platforms for ensuring flexibility in omnichannel distribution networks in urban areas	Cloud-based multi-plant management	
• Need for more precise technologies for location, both indoor and outdoor, e.g., GPS tracking systems • Inventory and routing problems to be faced with real-time, dynamic availability (and versatility) of data • More efficient communication and goods transportation along the overall chain with IoT	Location technologies for global sourcing	Technologies for sustainable sourcing and distribution in urban areas
• Fully integrated and well-developed communication infrastructure assuring the implementation of 5G • "There is the need to regulate 5G to solve interoperability problems and ensure basic data access, connecting fast (and in a reliable way) the whole supply chain" • Intelligent city logistics networks with high-connectivity infrastructure for late customization and distributed assembling of products in urban networks of small factories and FabLabs	Communication technologies (5G) for connection of urban production and distribution networks	
• Promoting efficient and sustainable urban logistics with light electric vehicles • Optimization of last-mile delivery with vehicles, drones, and sharing transportation models for more sustainable personalized shipments • Decentralized supply networks and local manufacturing cells arranged with swarm intelligent behavior • Improve energy storage and local production by developing "full local solutions"	Autonomous systems for sustainable last-mile delivery in urban areas	

TABLE A9 Coding of technologies and their applications enabling customer-driven supply chain.

Representative quotes/concepts	Technology application	Extent of technology application
• "Nowadays there is a high availability of plenty of data and the need to "digging" should be faced with innovative tools to interpret them correctly." • "New models and tools for gathering and handling a huge volume of data from customers through BDA and AI could be developed as "ahead-of-customer-thinking planning tools, with genetic algorithms developed from current artificial intelligence approaches" • "In the fashion sector, there is a growth of retrieving data from social media and wearable devices, using BDA and machine learning, to permit further the understanding of consumer shopping behavior and willingness to pay for personalized goods"	Analysis of demand variability and investigation of behaviors based on BDA, AI, and Smart wearable devices to create customer profiles	Technologies to detect and analyze customer and market needs and transform them into (personalized) products
• "Data science and IoT, through social sensors can have critical relevance, increasing the ability to learn customer preferences, habits and values, making it easier to tailor the SC better" • Cloud-based computer systems associated with data science could be essential to develop new customer data platforms relying on first-hand data, a persistent customer base, and high connectivity with current data management platforms • "In the consumer good sector, co-creative prosumer B2C and C2C platforms enable to connect consumers, professionals, and engineers in a seamless and frictionless customer journey"	Data collection through IoT (social sensors) and cloud-based platforms for the realization of customized products	
• "Additive manufacturing technologies can enable new opportunities for customization, lowering manufacturing costs and improving product performance. • "We need to adopt 3D printing for the realization of functional prototypes and customized components" • "The integration of additive and hybrid manufacturing will increase SC performance in terms of agility, responsiveness and reliability"	Manufacturing of customized products and components by Additive Manufacturing	
• "The adoption of the decentralized and encrypted data record can help our company to better address privacy concerns and be more transparent with our customers" • "Blockchain technology will permit us to implement innovative forms of consumer loyalty programs"	Distributed ledger/blockchain for handling multiple decision levels and improving customer relationship	Technologies for secure and trusted customer relationships

TABLE A10 Coding of technologies and their applications enabling fast reactive supply chain.

Representative quotes/concepts	Technology application	Extent of technology application
• "There is the need to collect data and better exploit them to support decision making and facilitate supply chains in facing unexpected events" • advanced AI models and tools for finding alternative actions for periodically changing trading barriers. • "In our supply chain a proper digital infrastructure would be useful to acquire data and build appropriate models to make predictions on supplier delivery"	Optimization of network design through data management with BDA and AI	Technologies for prompt reconfiguration of supply chain
• "Necessary to detect real-time disruptions and facilitate sharing of information along the automotive supply chain" • Investing in new sensoring systems along with the distribution network for trucks, products, etc.	Sensoring and location technologies for detecting of real-time disruptions	
• "As logistics providers we think it is important to extend functionalities of communication systems that are usually available at the factory level and to use them also for distribution and transportation processes" • "In case of disaster, it is necessary to have the capability to interact with stakeholders also outside the supply chain"	Multi-actor digital platforms to support interaction and share information	Technologies for sharing information across processes and actors
• "I think AI would allow my company to analyze a large amount of data to be faster in front of problems with my material flows • Alert systems to detect risks related to disruptions	AI predictive models for risk management	Technologies for risk management
• "Geopolitical risks need to be prevented with appropriate models" • Need to have a vision also on exogenous variables • Better interconnected and redundant infrastructure for supply chains across countries	Redundant infrastructure and intelligence for contingency plans	

TABLE A11 Coding of technologies and their applications enabling resource-efficient supply chain.

Representative quotes/concepts	Technology application	Extent of technology application
• Production of lot-one products at the local level only when they are needed, avoiding stocks and residual materials • "In our supply chain, we are testing AM to produce ad hoc single spare parts of equipment without the use of the related molds usually necessary in conventional manufacturing processes, avoiding transportation of components from suppliers to manufacturers"	Additive manufacturing (3D printing) for one-lot production	Technologies for optimization of supply chain operations
• Shared scheduling of production, distribution, and transportation services to optimize operations • Standardization of shared information to optimize resource allocation and procurements	Cloud-based platforms for shared operations management	
• Data collection from different points in the supply chain (machines, trucks, forklifts, ...) on procurements and consumption of raw materials and components • Information from among different plants and actors to avoid excessive inventory, errors in production, empty travels, fuel consumption, wastes	IoT for data collection	Technologies for monitoring and control of energy usage and waste
• Real-time analysis, monitoring, and control of energy consumption and carbon emissions along with the supply chain processes • "We were able to ensure the redistribution of energy among the actors of the symbiosis through an intelligent and more sustainable supply chain"	Big data analytics and artificial intelligence for intelligent energy usage	