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The preliminary supply chain lessons of the COVID-19 disruption—What is the role of digital technologies?

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Abstract
The purpose of this research is to analyse the current body of knowledge on the relationship between the COVID-19 pandemic and its implications for global supply chains and their management. This research seeks to understand how the COVID-19 event leads to impacts, lessons, and proposed solutions for the operations of global supply chains. This study is based on a structured review of publications released on or before 31 December 2020. It includes established academic publications but also those emerging primarily from academic institutions in trade magazines and on the wider internet. Specifically, four research questions are addressed: How and where are disruptions caused by COVID-19 understood to impact global supply chains? How does the literature portray supply chain lessons from the COVID-19-related disruptions? How does the literature portray the suggested resilience-driven solutions for the future operation of global supply chains? Finally, how are digital technologies proposed as part of resilience-driven solutions to the future operation of global supply chains? Concerning the findings, the study contributes by developing a new theoretical understanding of the ongoing collective supply chain lessons of the COVID-19 disruption. Six supply chain vulnerabilities, six solutions or resilience capabilities and seven technology clusters deemed particularly useful in mitigating future pandemic disruptions are identified. In addition, the interrelationships between the different elements are explored and understood as an ongoing learning process comprising a process of evoking vulnerabilities, a process of reacting and devising change and a process of implementing change. Based on these findings, a set of managerial implications and avenues for future research are proposed.

1 Introduction

Supply chains are inherently susceptible to disruptions that can affect their operations at various scales. Some disruptions are predictable, and enterprises can build risk management strategies to predict, assess, and mitigate them. However, unpredictable disruptions can have catastrophic consequences for entire supply chains. Such is the case of black swan events (Taleb 2007; Aven 2013). These events occur rarely but have large-scale implications for most aspects of society. In these cases, risk mitigation is harder to manage and can thus bring fewer benefits; therefore, supply chain managers must think of alternative strategies. Supply chain management research has proposed different forms of resilience capabilities and the re-design of supply chains to build resilience to minor and major disruptions (Han et al. 2020). The objective is to build supply chains that are robust to the advent of shocks and that can quickly respond and recover. However, a central question is whether the current known practices and the knowledge that we have, enabled us to fully comprehend and manage extreme events like the COVID-19 pandemic.

The outbreak of the coronavirus pandemic at the beginning of 2020 was a rare and catastrophic event for most supply chains around the world (Ivanov and Das 2020; Kumar et al. 2020; Sharma et al. 2020a, b; Van Hoek 2020). The event unfolded unpredictably during 2020, emerging in waves in different geographic locations. As a result, the pandemic exposed many new vulnerabilities of supply chains and caused a rare portfolio of simultaneous disruptions, resulting in ripple effects (Dolgui et al. 2018) and other forms of extreme disturbance. Epidemic outbreaks such as COVID-19, are a special case of supply chain risks that, besides simultaneously disrupting supply, demand, and

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logistics infrastructure, are also characterized by "simultaneous disruption propagation in the supply chain (i.e., the ripple effect) and epidemic outbreak propagation in the population" (Ivanov 2020).

Although we are now starting to understand the magnitude of this event and how it unfolded in different industries and the supply chains that connect them, the full nature and complexity of the event are still far from understood. Therefore, research that sets out to build a fuller picture of the COVID-19 pandemic and its multifaceted impact on supply chains is needed (Queiroz et al. 2020; Van Hoek 2020). It needs to be understood as a system of interrelated disruptions. It is also necessary to understand how the event led supply chain managers and academics to reflect on the inadequacies of existing supply chain structures and risk management practices. What was learned about the resilience capabilities embedded in the existing designs and practices in supply chains? Still another reflection is warranted, and this is related to the future and how these newly claimed insights unfold and lead to new solutions for building more resilience into supply chains. How can this devastating event be built into the memory of supply chains and supply chain management practices? What is the solution space suggested so far? One of the measures discussed in the practitioner and academic literature as promising is digitalization (e.g., Cahn 2020; Chowdhury et al. 2020; DeAngelis 2020). This study further aims to investigate how digital technologies affect resilience to pandemic-caused disruptions.

To address these calls for more insights into the event, this paper applies a structured literature review methodology and provides a comprehensive account of the current state of knowledge on the impacts of the COVID-19 pandemic on global supply chains. Specifically, four research questions are explored:

How and where are disruptions caused by COVID-19 understood to impact global supply chains?
How does the literature portray the supply chain lessons from the COVID-19-related disruptions?
How does the literature portray the suggested supply chain resilience-driven solutions for the future operation of global supply chains?
How are digital technologies proposed as part of resilience-driven solutions to the future operation of global supply chains?

The remainder of the paper is organised as follows. The first section presents the methodology of the review in terms of the structured literature review approach that is adopted. Then in Sects. 3, 4, 5, and 6, the four different parts of the structured literature review are presented. Section 7 presents the discussion and contributions. Section 8 presents recommendations for future research and managerial implications.

2 Review methodology

This paper is based on a systematic literature review. A systematic or structured review is an approach to literature reviews that "locates existing studies, selects, and evaluates contributions, analyses and synthesizes data, and reports the evidence in such a way that allows reasonably clear conclusions to be reached about what is and is not known" (Denyer and Tranfield 2009, p. 671). The aim of a systematic literature review is to inform practitioners about the current state of knowledge in a specific management area such that it can be used in decision making "by bounding available options" (Tranfield et al. 2003, p. 219).

Given the actuality of the coronavirus crisis, few peer-reviewed academic articles have discussed the effect of the pandemic on supply chains. For this reason, the literature search included several sources of information: EBSCOhost, Google Scholar, Industry/Market reports databases (Euromonitor/Passport and MarketLine) and Google searches.

First, a search was conducted on EBSCOhost to retrieve papers (academic and nonacademic) written in English that discussed the effects of the coronavirus crisis on supply chains. The search was performed and updated to include relevant articles published on or before 31 December 2020. Selected databases from EBSCOhost (Business Source Complete and Academic Search Elite) were searched using the following strings:

corona OR "COVID-19" OR "COVID" OR "coronavirus"* in *Title* AND *"supply chain" OR "supply chain management" OR "production" OR "operations" OR "logistics"* OR *"distribution" OR "sourcing"* in *Subject Terms.*

The search yielded 317 results. After reading the titles and abstracts, 55 articles were considered for full-text review, resulting in the final selection of 34 relevant sources. Second, a search was conducted to identify industry reports discussing the overall impact of the coronavirus pandemic on supply chains on the databases of *Euromonitor (Passport)* and *MarketLine.* The search terms "*coronavirus, COVID-19"* were combined sequentially with each of the terms *"supply chain," "supply chain management," "production," "operations," "logistics," "distribution" and "sourcing"* and yielded seven potentially relevant results. Third, a Google search was conducted, including the terms *coronavirus, covid-19, supply chain* and *professor or expert,* to identify short opinions of academics and experts in trade magazines or journals. Finally, an overall Google search was conducted using the search terms *coronavirus, COVID-19, supply chain and supply chain management* to retrieve other relevant sources of information, such as consultancy reports, trade magazines and websites. Through the last two steps, 21 potentially relevant sources were added to the sample. After the full-text reading of the articles, 53 articles were selected for review (see Fig. 1).

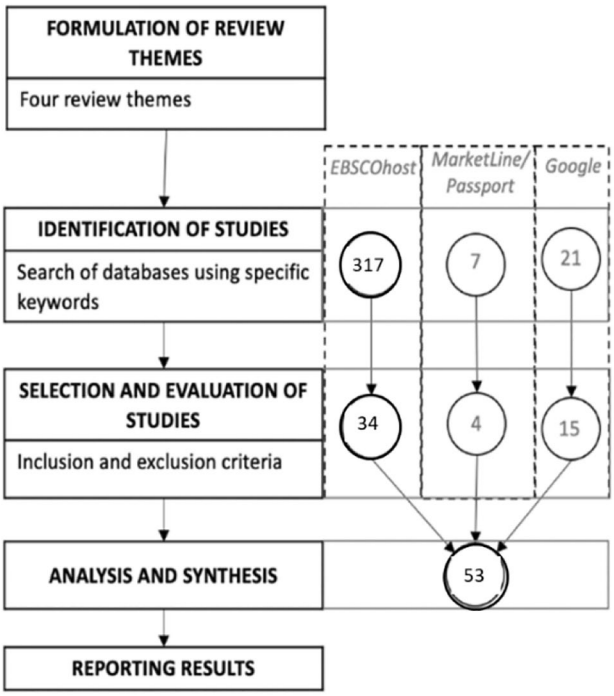

Fig. 1 Literature review method

The resulting sample was analysed using NVivo software. Top-level codes were created that corresponded to the themes described above. Forty-five of the articles in the review sample discussed the nature of the impacts of the COVID-19 pandemic on supply chains; 30 articles discussed lessons from the coronavirus disruption; 35 proposed solutions to increase the resilience of supply chains to future disruption; and 27 articles discussed digitalization as an enabler of the proposed solutions for increasing supply chain resilience. Then, within each of these broad themes, the data were coded inductively by discovering patterns and emerging themes.

To identify the areas of disruption, we used automatic text analysis, applying a combination of word frequency analysis and word occurrence analysis. Where word frequency analysis finds a top of the most often used words in the sample (by the total number of references), word occurrence analysis searches all files for specific words and gives detailed information on the number of files the word appears in and the total number of references in total and per file. Based on this information, we identified five major types of impact: manufacturing, supply, sales, logistics and people. The outcome of the automatic text analysis is provided in Table 1.

The following section presents the nature of the supply chain effects of COVID-19 disruption.

Table 1 Result of word frequency and word occurrence analysis in the sample

Supply chain area	Words	Sources		References
		N	%	N
1. Manufacturing	Manufacturing	45	*100%*	576
	Production	43	*96%*	738
	Operations	41	*91%*	518
2. Supply	Supplying	33	*73%*	118
	Sourcing	42	*93%*	336
	Procurement	21	*47%*	69
	Suppliers	45	*100%*	561
3. Logistics	Logistics	39	*87%*	532
	Transportation	42	*93%*	345
	Distribution	35	*78%*	151
	Delivery	37	*82%*	164
4. Demand	Demand	44	*98%*	543
	Sales	30	*67%*	155
5. People	People	36	*80%*	126
	Workers	23	*51%*	66
	Consumers	39	*87%*	186
	Buyers	26	*58%*	77
TOTAL		**45**		

3 Nature and supply chain effects of COVID-19 disruption

In this section, the paper explores how and where disruptions caused by COVID-19 are understood to impact global supply chains.

Emerging research on epidemic outbreaks highlights that epidemics are a special case of supply chain risks characterized by the simultaneous disruption of three supply chain components: supply, demand, and logistics infrastructure (Ivanov 2020). Several articles in the review sample noted the sequential or concurrent effect of COVID-19 on supply chains in these three supply chain components (Ivanov and Das 2020; Kumar et al. 2020; Sharma et al. 2020a, b); however, most articles focused on the effects on only one or two of them.

An important aspect of disruptions is their propagation through the supply chain; instead of being contained in one area, the disruption cascades to other parts, affecting the performance of the entire supply chain. This phenomenon is known as the ripple effect (Dolgui et al. 2018). The several effects of the COVID-19 disruption did not occur simultaneously but were part of the myriad of ripple effects sent through the supply chain by significant shocks, such as the closure of manufacturing operations in China and the subsequent closure of ports in China.

The analysis of the review sample revealed five areas of the supply chain that were affected by the COVID-19 pandemic: manufacturing, supply, logistics, demand, and people. The following subsections synthesize the effects on each of these five areas.

3.1 Manufacturing effects

One of the most significant supply chain disruptions caused by the COVID-19 pandemic affected manufacturing due to factory shut-downs (Baumgartner et al. 2020; Cahn 2020; Kumar et al. 2020; Queiroz et al. 2020). The disruptions started with the production and assembly halt for Chinese firms on January 25th 2020 and February 3rd 2020 in an attempt to contain the spread of the virus (Ivanov 2020). Over January 2020 and February 2020 combined, industrial production in China was reduced by 13.5%, which was a higher drop than both the SARS outbreak of 2002/2003 and the financial crisis of 2008/2009 (Seric et al. 2020).

The effects of halting production and assembly are propagated through global supply chains in several ways. Firstly, European and North American industries that were highly reliant on supplies from China had to also temporarily halt production due to the component shortages that ensued from the production halt in China (Liuima 2020a; Zhu et al. 2020). Due to long supply lead times by sea, the effects were first felt by manufacturers in Europe and North America in mid-March 2020 (Haren and Simchi-Levi 2020).

Restarting production in China was a slow and challenging process. A survey conducted by the Institute of Supply Management (ISM) at the end of February 2020 and the beginning of March 2020 revealed that Chinese manufacturers were working at 50% capacity, with 56% of normal staff (Ivanov and Das 2020; Templeton 2020). The slow return to full productivity was also compounded by disruptions in their domestic supply lines, as assembly had to wait for suppliers to restart operations (Van Hoek 2020). As the virus spread to the West, similar challenges were felt by North American and European manufacturers: the delayed return of workforce and lower worker attendance due to infected employees, safe distancing measures within the factory, and restricted mobility of personnel due to traffic restrictions slowed down the recovery of production (Agrawal et al. 2020; Kilpatrick and Barter 2020; OECD 2020).

3.2 Supply effects

The most often discussed effect on supply was drastic reductions in the availability of supplies, rendering firms unable to optimally balance supply and demand (Ivanov and Dolgui 2020). Hassoun and Mawet (2020) highlighted that even critical activities faced significant supply disruptions due to production shutdowns at suppliers.

Initially, the most affected supply chains were those that relied solely or heavily on inputs from China (Haren and Simchi-Levi 2020; Lin and Lanng 2020; Zhu et al. 2020); it is estimated that 51,000 global companies have one or more tier-1 suppliers, and five million have one or more tier-2 suppliers in the Wuhan region (Ivanov 2020; Kilpatrick and Barter 2020). ISM surveys revealed that 62% of US businesses experienced significant delays in receiving orders from China (Templeton 2020), quantified as up to double lead times (Ivanov and Das 2020).

Several industries were discussed in the articles reviewed as being highly impacted: prescription drugs, high technology, electronics, machinery, and automotive (Baumgartner et al. 2020; Cahn 2020; Haren and Simchi-Levi 2020; Ivanov and Das 2020; Kilpatrick and Barter 2020; Liuima 2020a, b; Zhu et al. 2020). China produces 70% of the active ingredient inputs for prescription drugs (Liuima 2020a; Zhu et al. 2020) and is also the largest manufacturer of high-tech goods. However, the most impacted industry, and the one expected to withstand long-term effects, is the automotive industry due to its complex and multi-tiered supply chain, which relies on a huge number of independent global suppliers and just-in-time delivery practices (Baumgartner et al. 2020; Liuima 2020a; Poole 2020).

Starting from March 2020, when Chinese manufacturing re-started and Europe and North America started imposing lockdowns, the reverse effect was observed. Chinese manufacturers started experiencing shortages of inputs from suppliers in Europe and North America, working below capacity (Liuima 2020a). Asian manufacturers were also affected by internal supply challenges, as they had to wait for their suppliers to ramp up production before they could restart assembly (Van Hoek 2020). Even food manufacturers started stocking up supplies to mitigate possible supply shortages due to product expiry (Chowdhury et al. 2020). Farmers face supply challenges due to the restricted access to essential supplies, such as fertilizer, seeds, and insecticide (Quayson et al. 2020).

Another global procurement challenge regards the shortage of personal protective equipment (PPE), which is necessary both for medical workers and for industrial workers (Nodar 2020; OECD 2020; Queiroz et al. 2020). However, the shortage is not considered a supply-side issue due to the extremely high reliance on Chinese suppliers of PPE but a demand shock. OECD (2020) highlights that given the unprecedented surge in demand for PPE equipment, even local suppliers would have been unable to produce the necessary amount demanded.

3.3 Logistics effects

The epidemic outbreak in China and its subsequent spread towards the West has broken transportation links between suppliers, production facilities, and customers (Kumar et al. 2020)

by reducing the availability of the different transportation modes even when suppliers were able to fill orders (Templeton 2020).

The shipping industry faced disruptions in all transportation sectors: sea, air, and road (Rojas 2020). Sea/ocean freight was significantly disrupted by the closure of port operations in China on February 11th 2020. According to the UN Conference on Trade and Development, China is home to seven out of the ten busiest container ports in the world (MarketLine 2020), and Wuhan, the region most affected by the pandemic in China, is "home to the largest inland port in the country" (Kilpatrick and Barter 2020). Only in February 2020 did departures from Chinese ports decrease by 20% (Haren and Simchi-Levi 2020). This caused shipping companies to increase blank sailings (Nodar 2020; Rojas 2020), thus skipping ports or entire strings of ports altogether. The reduction in ports' operating hours caused delays for truckers in picking up and dropping off cargo (Rojas 2020).

The shutdown of production operations implied that companies stopped accepting deliveries from their suppliers, which increased the short-term storage of goods (Paeth 2020) and caused further congestion at ports (Rojas 2020; Sharma et al. 2020b; Templeton 2020). Airfreight was significantly disrupted by restrictions on the movement of people across countries and the cancellation of passenger flights, which slashed the availability of belly cargo (Nodar 2020; Rojas 2020; Zhu et al. 2020). Border crossing restrictions and sanitary measures at borders also affect road transportation (Rojas 2020). Together with restricted operations hours at ports, this caused significant delays in reaching customers (Rojas 2020).

All of these effects on the different transportation modes decreased freight volumes (Cahn 2020; Kumar et al. 2020; Szakonyi 2020), causing some smaller companies to go off the market and subsequently lowered overall capacity (Cahn 2020; Chowdhury et al. 2020; Nodar 2020; Rojas 2020) and ultimately increased shipping costs (Cahn 2020; Rojas 2020). Reaching end consumers was impacted by the unexpected significant surge in online demand, which challenged businesses with insufficient inventory allocated to the online channel and caused severe shortages of last-mile delivery capacity (Agrawal et al. 2020; Cahn 2020; Ketchen and Craighead 2020; Kilpatrick and Barter 2020;). The negative effect was compounded by virus containment measures, which implied new requirements for packaging and contactless last-mile delivery (Agrawal et al. 2020). Liuima (2020a) highlighted that the inability to reach end-customers caused significant food waste and loss of revenues for food producers.

3.4 Demand effects

Most articles in the review described the effects of the coronavirus crisis on demand as double-sided: while some industries experienced significant surges in demand, others suffered from severe reductions (Cahn 2020; Johnson 2020a; Sharma et al. 2020a; Van Hoek 2020). Increased demand was reported for essential goods (Kumar et al. 2020; Van Hoek 2020), such as some grocery items, and for products protecting people from the virus, such as masks, hand sanitisers, cleaners (Cahn 2020; Chowdhury et al. 2020; Council and Uberti 2020; Kumar et al. 2020; Sharma et al. 2020a), and for some medications, herbs, and vitamins (Donthu and Gustafsson 2020). Grocery retailers were faced with panic buying from consumers worried about shortages of essential products (Cahn 2020; Van Hoek 2020; Zhu et al. 2020), causing empty supermarket shelves (Cahn 2020; Laluyaux 2020). Due to lockdowns, a large amount of the food and beverage products stocked in retail shops to meet the peak demand season (March–June 2020) were expected to expire (Chowdhury et al. 2020). Products most affected were meat and toilet paper (Cahn 2020; Council and Uberti 2020), bread, eggs, milk (Sharma et al. 2020a), and ground coffee (Paeth 2020). Lockdown measures and working from home also increased the demand for some non-essential items, such as snacks and alcohol, cleaning products (Donthu and Gustafsson 2020), and streaming services (Strange 2020).

Decreased demand is reported for most other product categories and is a result of economic uncertainties and virus containment measures (Liuima 2020a; Poole 2020). Consumer electronics faced steep reductions in demand (Haren and Simchi-Levi 2020; Liuima 2020a), together with apparel and accessories (Van Hoek 2020). In the B2B sector, the shutdown of plants reduced the demand for machinery (Liuima 2020a) and chemical products used in automotive production (Cahn 2020).

The reduction in the consumption of services as a result of virus containment policies, such as suspension of events and closure of restaurants, caused reduced demand for food items sold through this B2B channel, but the overall effect on demand for food items seems to be positive due to the increase in consumer demand. For this reason, the effect on demand for food is sometimes referred to as a shift in demand (Johnson 2020a; OECD 2020; Shih 2020), as food demand overall increased, but through a smaller number of channels (Johnson 2020a).

Another effect on demand was a shift in consumer behaviour, such as an increase in weekday shipping during the lockdown periods and a preference for bulk packages of particular products (Council and Uberti 2020). The most significant effect on consumer behaviour was the increase in online shopping and home delivery (Paeth 2020; Strange 2020), which is expected to become the new normal for consumers (Paeth 2020).

3.5 People effects

The epidemic propagation through the population happens simultaneously with the disruption propagation in the

supply chain (Ivanov 2020). The infection of people and the measures taken to protect the population from infection can become the origin of disruption propagation throughout the supply chain. Within the supply chain, people are both an important resource as workers and as consumers of products. Therefore, effects on the supply chain from a people perspective can stem from both workers and consumers.

Consumers can drive effects through the supply chain in different ways: by causing variability of demand and ensuing demand–supply imbalances due to sudden panic buying (Cahn 2020; Van Hoek 2020; Zhu et al. 2020) and to changing consumption patterns (Council and Uberti 2020) or by shifting demand channels towards more online shopping (Paeth 2020; Strange 2020), thus causing issues for businesses not flexible enough to adapt delivery networks quickly (Paeth 2020).

However, the most significant impact stemming from people-related issues during the coronavirus crisis was related to workers. Labour shortages ensued during the pandemic from either people becoming infected, measures to protect workers' health, or restrictions on the movement of people (Agrawal et al. 2020; George et al. 2020; Sharma et al. 2020b). In a McKinsey survey of Asian manufacturers, reductions in worker availability were mentioned as the third most significant impact on their operations (30% of respondents) after demand and supply shocks (Agrawal et al. 2020).

People working in offices started working from home (George et al. 2020; Nodar 2020; Strange 2020), which caused fears of decreasing productivity, compounded by the closure of schools and the fact that parents had more difficulties balancing work and personal life (Strange 2020). For people in services that were not able to work from home, productivity concerns were fuelled by workers' concerns for their health (George et al. 2020).

In production and delivery, when work wasn't restricted by public policies, companies had to trade-off protecting the health of their workers by closing facilities or reducing hours and maintaining operational viability, already affected by supply and demand shocks (Alicke et al. 2020; Council and Uberti 2020; Strange 2020). Within production facilities, safe distancing measures reduce productivity (Agrawal et al. 2020; OECD 2020). In food production (agriculture), the reduced availability of seasonal migrant workers causes significant food waste and a loss of revenues for companies (Liuima 2020a; Sharma et al. 2020b). Restrictions on cross-border movement also affected industries like the global machinery industry, where specialists could not travel to install or repair equipment for their customers (Liuima 2020a).

Delivery is severely affected across all transportation modes because it depends on people for moving goods (OECD 2020; Strange 2020). Workers infected with the virus, or even workers' fears of infection, caused labour shortages, which ultimately restricted the flow of goods through the supply chain (Kumar et al. 2020; Rojas 2020). Some companies have replaced the missing workforce with autonomous shuttles and drones to be able to continue delivery operations (Sharma et al. 2020a). On the sales side, business models that relied on human contact were the ones that were most affected by the pandemic (Baumgartner et al. 2020).

A synthesis of the reported immediate effects of the COVID-19 crisis on global supply chains is provided in Fig. 2.

4 Lessons from the COVID-19 disruption

In this section, the paper explores how the literature portrays the supply chain lessons from the COVID-19 related disruptions. Table 2 provides a list of the sources discussing each type of lesson.

Based on the analysis of the identified literature sample, one of the most often mentioned lesson from coronavirus disruption is the historical over-reliance on cost efficiency in designing supply chains (e.g., DeAngelis 2020; El Baz and Ruel 2020; Haren and Simchi-Levi 2020; Garner 2020). Many of the other lessons discussed in the review sample, such as the risks brought by globalization (e.g., Cordon and Buatois, 2020; El Baz and Ruel 2020; Fonseca & Azevedo 2020), including an over-reliance on Chinese supplies (e.g., Lin and Lanng 2020; Liuima 2020a, b; MarketLine 2020), and lack of flexibility (e.g., Cordon and Buatois 2020; Sharma et al. 2020a; Szakonyi 2020) are consequences of the prioritization of cost efficiency in supply chain design. Another of the most frequently mentioned lesson is the need for visibility into the supply chain (e.g., Baumgartner et al. 2020; Fonseca and Azevedo 2020; Haren and Simchi-Levi 2020), followed by the need to be prepared for disruptions (e.g., Kilpatrick and Barter 2020; Lapide 2020; Rice 2020) and the interconnectivity of supply chains (Ivanov and Das 2020; Kilpatrick and Barter 2020).

The quest for cost-efficiency motivated companies to pursue strategies such as lean manufacturing, offshoring, and outsourcing (Haren and Simchi-Levi 2020) which during the pandemic resulted in the inability to continue operations due to the different shocks in manufacturing, supply, and logistics. Therefore, the coronavirus crisis taught supply chain managers that the cost-optimality of supply chains has to be balanced with preparedness, responsiveness, and resilience (DeAngelis 2020; Garner 2020; Haren and Simchi-Levi 2020; Zhu et al. 2020).

Globalized supply chains were vulnerable to manufacturing and port operation stoppages in China (Liuima 2020a), following disruptions in the West and overall disruptions in logistics caused by virus containment measures (Liuima

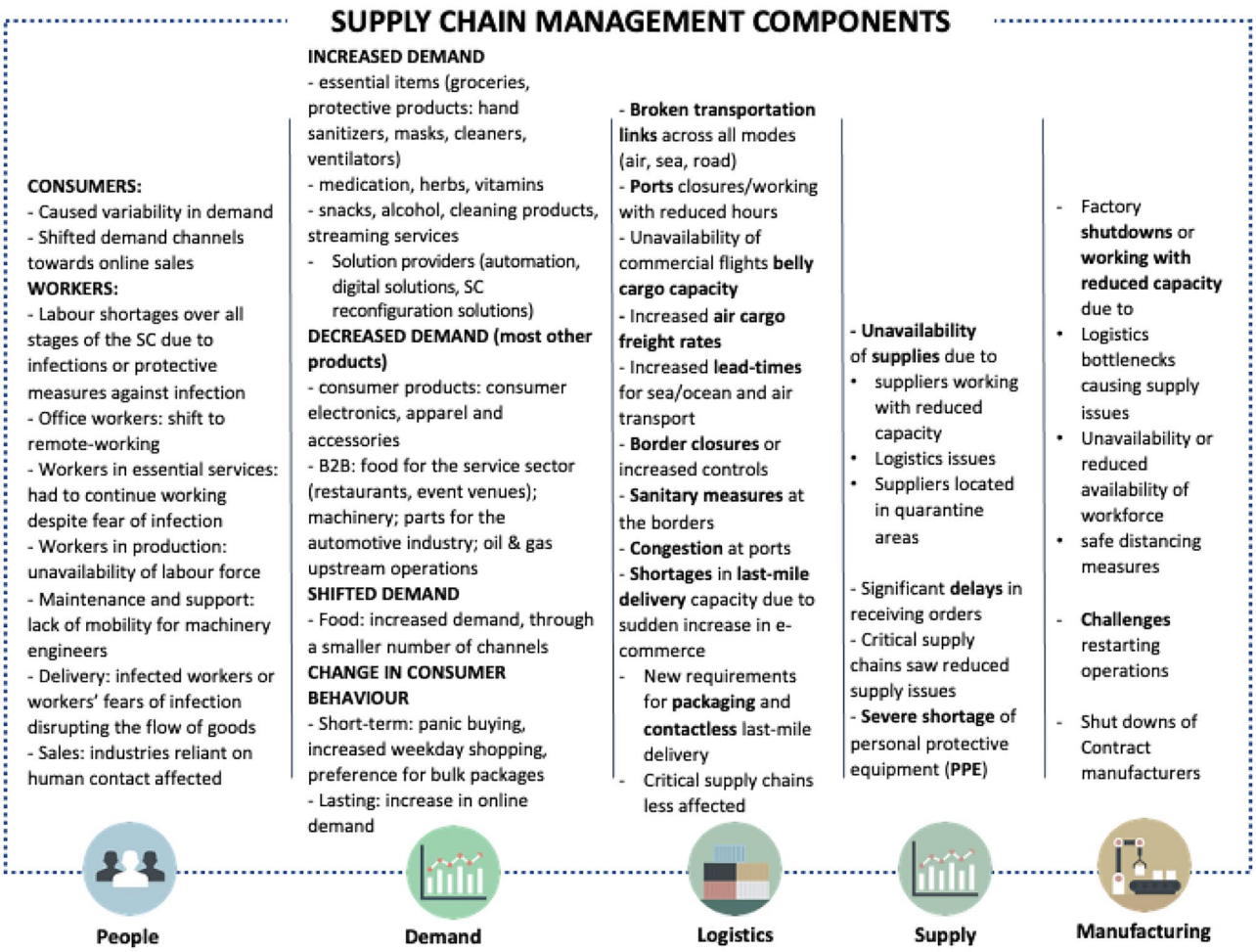

Fig. 2 An overview of the reported effects of the COVID-19 crisis on global supply chains

2020b). This reliance on global suppliers, particularly Chinese suppliers, is attributed to vulnerabilities related to a lack of flexibility in the supply base (Lin and Lanng 2020; Sharma et al. 2020a; Zhu et al. 2020). Another form of lack of flexibility discussed is difficulty in responding to demand and supply shocks (Cordon and Buatois 2020; Szakonyi 2020), which is known in the resilience literature as responsiveness or agility.

Regarding the issue of globalisation, global supply chains are also portrayed as a solution rather than a bottleneck for the supply of essential goods during a crisis (OECD 2020). One example is South Korea (which before the pandemic was not one of the main exporters of in vitro diagnostic tests), ramping up production to relieve the severe global shortage of testing equipment.

Another important lesson was the importance of visibility in supply chains beyond tier-one suppliers. This is particularly relevant for industries with very complex supply chains, such as the automotive industry (Baumgartner et al. 2020). The disruption in Asia was difficult to assess and manage due to the lack of transparency over indirect suppliers that might be located in Asia (Haren and Simchi-Levi 2020). Visibility is also important for transportation companies during a disruption to locate their cargo and monitor possible delays (Johnson 2020a).

The crisis also revealed the extent of interconnectivity between supply chains and the possibility of disruptions occurring from sources outside the immediate supply chain (Kilpatrick and Barter 2020). Sometimes the crisis even provoked dilemmas, where it was difficult to determine the most essential supply chains to ensure survivability. One example is related to suppliers in the automotive sector, some of which are also producers of valves for respirators (Ivanov and Dolgui 2020).

Overall, experts recognize the importance of preparedness for disruptions as options become very limited once the disruption is in full swing (Rice 2020). Lapide (2020) highlights that the lack of planned quick response programmes caused avoidable long-term shortages of FMCG goods, which saw a big spike in demand. On the other hand,

Table 2 Sources discussing lessons from the COVID-19 disruption

Lessons	Symptom / Vulnerability	Sources
Over-reliance on cost-efficiency in supply chain design	The historical overreliance on cost-efficiency has made supply chains vulnerable to pandemic disruptions	DeAngelis (2020); El Baz and Ruel (2020); Haren and Simchi-Levi (2020); Garner (2020); Kilpatrick and Barter (2020); Lin and Lanng (2020); Seric et al. (2020); Shih (2020); Zhu et al. (2020)
Globalized supply chains	Globalized supply chain designs, including high dependence on China has made supply chains vulnerable to pandemic disruptions	El Baz and Ruel (2020); Cordon and Buatois (2020); Fonseca and Azevedo (2020); Handfield et al. (2020); Lin and Lanng (2020); Liuima (2020a, b); MarketLine (2020); OECD (2020); Seric et al. (2020); Van Hoek (2020); Zhu et al. (2020)
Lack of flexibility	Lack of supply chain flexibility in e.g. sourcing/supply and manufacturing has made supply chains vulnerable to pandemic disruptions	Cordon and Buatois (2020); Sharma et al. (2020a); Szakonyi (2020); Zhu et al. (2020)
Lack of visibility	Lack of visibility in the form of little knowledge of the status of operating assets and the environment has made supply chains vulnerable to pandemic disruptions	Baumgartner et al. (2020); Fonseca and Azevedo (2020); Haren and Simchi-Levi (2020); Johnson (2020a); Sharma et al. (2020a); Zhu et al. (2020)
Lack of preparedness for disruptions	The general lack of preparedness for supply chain disruptions, in general, has made the supply chain vulnerable to pandemic disruptions	Kilpatrick and Barter (2020); Lapide (2020); Rice (2020); Van Hoek (2020)
Inter-connectivity of supply chains	The interconnectivity between supply chains disruptions occurring from sources outside the immediate supply chain has made the supply chain vulnerable to pandemic disruptions	Ivanov and Das (2020); Ivanov and Dolgui 2020; Kilpatrick and Barter (2020)

companies that had proactively invested in supply chain risk management and business continuity strategies were better prepared to respond to the crisis (Kilpatrick and Barter 2020).

5 Proposed solutions based on COVID-19 disruption

In this section, the paper explores how the literature portrays the suggested supply chain resilience-driven solutions to the future operation of global supply chains.

Based on our analysis of the literature, investments in improved supply chain risk management practices to increase supply chain resilience emerged as one of the most often mentioned proposed solutions to future pandemic events (Belhadi et al. 2020; Sharma et al. 2020b). This includes supply chain stress tests as a proposed new post-Covid 19 norm of managing (Cordon and Buatois 2020), and the development of risk-recovery contingency strategies (Handfield et al. 2020). It also means radical reorganisation to integrate risk management into all the organisation's decision-making processes (DeAngelis 2020). A pivotal role should be played by supply chain risk identification as a foundation for the whole supply chain risk management process (El Baz and Ruel 2020).

Increasing supply chain flexibility in different forms is also highlighted by multiple contributions as an extremely important solution. Particularly multiple sourcing, aimed at reducing supply vulnerabilities arising from reliance on suppliers is mentioned by multiple contributions (e.g., Cahn 2020; Cordon and Buatois 2020; DeAngelis 2020). However, the request for increased supply chain flexibility also concerns manufacturing flexibility in layout and execution and employee flexibility to work and adjust their work (Cahn, 2020).

Another frequently mentioned solution is a need to increase supply chain visibility (e.g., Agrawal et al. 2020; Baumgartner et al. 2020; Cahn 2020). Some articles focus only on visibility in the upstream supply chain, while others discuss end-to-end visibility in the supply chain to be more responsive. Mapping the supply chain is often discussed as a tool for increasing visibility (Choi et al. 2020; Ivanov and Das 2020; MarketLine 2020; Poole 2020; Rice 2020; Shih 2020; Van Hoek 2020).

Collaboration among supply chain members is discussed as an important lever in preparing for and responding to disruptions, as a joint effort to monitor disruptions, build warning systems (Alicke et al. 2020), manage risks (Sharma et al. 2020b), and, overall, come up with innovative solutions to build more robust systems (Belhadi et al. 2020; Garner 2020). Belhadi et al. (2020) note that goals and information sharing among supply chain members can contribute to powerful coordinated strategies, which, in turn, foster faster recovery. This, however, requires that supply chains overcome their current transactional type of engagement and move towards aligning, building trust

and sharing both losses and gains (Choi et al. 2020; Chowdhury et al. 2020; de Sousa Jabbour et al. 2020; Sharma et al. 2020a). Ketchen and Craighead (2020) highlight that disruptions can become opportunities for improving buyer–supplier relationships due to the service recovery paradox.

A third of the articles mentioned regionalization (sometimes even localization) as a solution to overreliance on overseas suppliers or dependence of governments of another country (e.g., Belhadi et al. 2020; Cordon and Buatois 2020; de Sousa Jabbour et al. 2020; Handfield et al. 2020); however, three of the articles mentioned that companies should not completely back off from globalization, but merely balance offshoring with near-shoring to de-risk the supply chain (Shih 2020; Van Hoek 2020; Zhu et al. 2020). In the case of agricultural supply chains, regionalization was discussed in terms of shortening supply chains by focusing on smart farming (Sharma et al. 2020b).

Redundancy was mentioned as a proactive measure in preparing for disruption or as a response to supply shocks (e.g., DeAngelis 2020; Fonseca and Azevedo 2020; Garner 2020); Ivanov and Das (2020) suggest that epidemic outbreaks are better managed through building capabilities for situational responses to real-time changes (which is a form of responsiveness), rather than proactive redundancies, and propose building flexible redundancies. Ketchen and Craighead (2020) contend that the specificity of pandemics requires transiliency, i.e., "the ability to simultaneously restore some processes and change—often radically—others" (p. 1335).

All the above strategies should be considered components to be evaluated when redesigning supply chains to reduce vulnerabilities to such large-scale disruptions (de Sousa Jabbour et al. 2020; Queiroz et al. 2020; Rice 2020; Sharma et al. 2020a, b). Thus, based on our literature synthesis we found multiple and partly overlapping propositions on how to prepare for future pandemic events. The proposed solutions are in nature not new, as they all relate to previously identified resilience competencies (e.g., Pettit et al. 2013). However, what might be considered as new is the comprehensiveness and diversity of suggestions, as this is in principle all reactions to only one risk event. This highlights the extensiveness of the event, not at least in how its implications are collectively being perceived. Table 3 provides a complete list of articles mentioning each proposed solution.

Table 3 Sources discussing proposed solutions

Proposed Solution	Description of proposed SCM change	Sources
Risk management	More focus on resilience and strengthening risk management practices	Alicke et al. (2020); Belhadi et al. (2020); Chowdhury et al. (2020); Cordon and Buatois (2020); DeAngelis (2020); De Sousa Jabbour et al. (2020); El Baz and Ruel (2020); Fonseca and Azevedo (2020); Handfield et al. (2020); Ketchen and Craighead (2020); Kumar et al. (2020); OECD (2020); Poole (2020); Queiroz et al. (2020); Sharma et al. (2020a; b); Strange (2020); Van Hoek (2020)
Flexibility	More flexible supply chains, including flexible sourcing/supply and flexible manufacturing	Cahn (2020); Cordon and Buatois (2020); Liuima (2020a, b); DeAngelis (2020); Donthu and Gustafsson (2020); Ivanov and Das (2020); Baumgartner et al. (2020); Kilpatrick and Barter (2020); Kumar et al. (2020); Lin and Lanng (2020); OECD (2020); Queiroz et al. (2020); Rice (2020); Sharma et al. (2020a); Zhu et al. (2020)
Visibility	More knowledge of the status of operating assets and the environment	Agrawal et al. (2020); Baumgartner et al. (2020); Cahn (2020); Choi et al. (2020); Cordon and Buatois (2020); Poole (2020); Ivanov and Das (2020); Kilpatrick and Barter (2020); MarketLine (2020); OECD (2020); Rice (2020); Sharma et al. (2020a); Shih (2020); Van Hoek (2020); Zhu et al. (2020)
Collaboration	Strengthening existing supply chain relationships, and building new ties with strategic partners	Belhadi et al. (2020); Choi et al. (2020); Chowdhury et al. (2020); De Sousa Jabbour et al. (2020); El Baz and Ruel (2020); Garner (2020); Kilpatrick and Barter (2020); Alicke et al. (2020); Sharma et al. (2020a, b)
Regionalization	Simplifying supply chain design, and moving some production back or nearshore	Belhadi et al. (2020); Cordon and Buatois (2020); de Sousa Jabbour et al. (2020); Fonseca and Azevedo (2020); Handfield et al. (2020); Liuima (2020a, b); Rice (2020); Seric et al. (2020); Sharma et al. (2020b); Shih (2020); Strange (2020); Van Hoek (2020); Zhu et al. (2020)
Redundancy	Strategically working to establish different forms of redundancies in the supply chain	DeAngelis (2020); Fonseca and Azevedo (2020); Garner (2020); Ivanov and Das (2020); Liuima (2020b); OECD (2020); Shih (2020); Zhu et al. (2020)

6 Digitalization as a solution to building resilience

Besides the solutions discussed in the previous section, investment in digital solutions emerged as the most often discussed long-term strategy for protecting the supply chain from large-scale pandemic-caused disruptions. Therefore, we in this section explore the fourth and final research question, namely, how digital technologies are proposed as part of the resilience-driven solutions to the future operation of global supply chains.

Digital solutions promise to provide flexibility, connectivity, visibility, and agility, all of which are resilience capabilities that can better prepare supply chains to manage future disruptions, (Belhadi et al. 2020; Cahn 2020; Chowdhury et al. 2020; DeAngelis 2020; Liuima 2020a; Sharma et al. 2020a; Shih 2020). The relationship between the proposed solutions presented in the previous subsection and digital technologies is shown in Table 4. In our analysis, we found that four of the identified six major proposed solutions based on COVID-19 disruption, can to some extend be enabled or enhanced by different types of digital technologies. This section discusses how these technologies, based on our literature synthesis and analysis, are found to enhance these four important resilience capabilities: flexibility, visibility, risk management and collaboration.

Several technologies can increase flexibility in the supply chain. IoT-enabled production lines can increase production capacity (Agrawal et al. 2020; Kumar et al. 2020), while IoT-enabled delivery can optimize logistics processes by anticipating bottlenecks, accelerating gate-in and gate-out processes, and optimizing inventory (De Sousa Jabbour et al. 2020; Johnson 2020b; Sharma et al. 2020a). Together with artificial intelligence and machine learning, they can also assist in quickly finding alternative suppliers in case of disruption (Lin and Lanng 2020; Zhu et al. 2020). Process and physical automation (robotics, Robotics Process Automation (RPA), automated guided vehicles) can supplement or replace labour capacity in manufacturing and delivery, improve monitoring, and increase efficiency (Agrawal et al. 2020; Chowdhury et al. 2020; DeAngelis 2020; De Sousa Jabbour et al. 2020; George et al. 2020; Ivanov and Das 2020; Liuima 2020a; Shih 2020; Szakonyi 2020). Three-dimensional printing can increase manufacturing flexibility by enabling the in-house production of complex, low-volume spare parts and customized products (Liuima 2020a) which will reduce transportation costs by enabling production closer to the customer, as well as reducing dependency on suppliers (Shih 2020). Augmented reality can enable remote assistance in equipment installation and maintenance, replacing the need for travel (Agrawal et al. 2020; De Sousa Jabbour et al. 2020).

Visibility in the supply chain, another important resilience capability, can be enhanced by combining tracking and tracing technologies (such as Radio-frequency identification (RFID), blockchain, digital twins, geolocation, satellites and drones) with artificial intelligence and advanced analytics (such as big data analytics). Together, these digital technologies can enable real-time tracking of demand and goods locations during transportation, thus enhancing planning capabilities and ultimately increasing responsiveness (Agrawal et al. 2020; Cordon and Buatois 2020; George et al. 2020; Johnson 2020b; Kilpatrick and Barter 2020; Queiroz et al. 2020; Raghu 2020; Sharma et al. 2020a, b). Supply chain mapping software can provide end-to-end visibility into the supply chain and assist in quickly identifying the dependency on critical suppliers located in affected areas, especially when combined with advanced analytics (Alicke et al. 2020).

The ability to enhance supply chain risk management can also be increased through the use of artificial intelligence, machine learning and advanced analytics which can help in automatically sensing demand volatility and in predicting potential disruptions and delays, which will increase supply chains' readiness for unexpected events (Council and Uberti 2020; DeAngelis 2020; George et al. 2020; Kilpatrick and Barter 2020; Kumar et al. 2020; Laluyaux 2020; Lin and Lanng 2020; Sharma et al. 2020a; Zhu et al. 2020). Also, recovery after a pandemic-caused disruption can be strengthened because of improved demand replanning capability (e.g., Agrawal et al. 2020).

Concerning collaboration, some digital technologies hold the potential to seemingly bridge tiers in the supply chain. One example is that some technologies, such as augmented reality, enable collaboration over distances, which is important when travel is highly constrained in the pandemic situation (Agrawal et al. 2020; De Sousa Jabbour et al. 2020). Another example is that some forms of traceability technologies such as blockchains may provide visibility that enhances collaboration between partners embedded in the platform. Finally, the digitalization of the supply chain through the integration of all supply chain members to increase collaboration leads to the creation of a digital supply network (DSN) or a digital twin of the physical supply chain, where all communication and information across the network is tracked, providing end-to-end visibility and improving collaboration (Agrawal et al. 2020; Cahn 2020; Zhu et al. 2020). DSNs are enabled by all the other technologies enumerated above.

A comprehensive presentation of the applications of the most often mentioned technologies, their role in building supply chain resilience, and the articles discussing them are provided in Table 4.

Table 4 The role of digital technologies in building supply chain resilience to COVID-19 disruption, as portrayed in the literature

Technologies	Applications	Findings		Sources
		Effect of technology	**Impact on another potential pandemic**	
Internet of Things (IoT)	• IoT-enabled production lines • IoT-enabled delivery	Flexibility	Some disruptions can be avoided or reduced by enabling more flexible production capacity and better utilisation of inventory and logistics processes	Agrawal et al (2020).; DeAngelis (2020); De Sousa Jabbour et al. (2020); George et al. (2020); Johnson (2020b); Kilpatrick and Barter (2020); Kumar et al. (2020); Lin and Lanng (2020); Sharma et al. (2020a; b); Zhu et al. (2020)
Automation	• Robotics (physical automation) in manufacturing and warehousing • Automated Guided Vehicles (AGV) • Process Automation (data collection, quality control, inspection)	Flexibility	Some disruptions can be avoided by supplementing or replace labour capacity in manufacturing and delivery, thereby reducing infections and potential stops in the supply chain flow of material	Agrawal et al. (2020); Belhadi et al. (2020); Cahn (2020); Chowdhury et al. (2020); De Sousa Jabbour et al. (2020); Liuima (2020a); George et al. (2020); Shih (2020); Szakonyi (2020)
3D Printing	• Production of spare parts • Manufacturing of customised products • Feasible for complex, low-volume parts, not for mass manufacturing.	Flexibility	Some disruptions can be avoided by enabling in-house production of complex, low-volume spare parts and customized products which will reduce the need for transportation/travel through enabling production closer to the customer, as well as reducing dependency on suppliers	Liuima (2020a); Kilpatrick and Barter (2020); Kumar et al. (2020); Queiroz et al. (2020); Shih (2020)
Augmented reality	• Remote assistance in equipment instalment, maintenance	Flexibility Collaboration	Some disruptions can be avoided by enabling remote assistance in equipment installation and maintenance, replacing the need for travel in times where borders are closed or travel constrained	Agrawal et al. (2020); De Sousa Jabbour et al. (2020)
Traceability technologies	• RFID tags • Blockchain • Cell phone geolocation • Satellites • Drones	Visibility Collaboration	Some disruptions can be avoided by enabling better knowledge about the location of products and capacity in real-time, as well as by using real-time demand information and direct information exchange with supplier and customers	Agrawal et al. (2020); Belhadi et al. (2020); Raghu (2020); Cordon and Buatois (2020); George et al. (2020); Johnson (2020a, b); Kilpatrick and Barter (2020); Quayson et al. (2020); Queiroz et al. (2020); Sharma A et al. (2020a, 2020b)
Artificial intelligence Machine learning Advanced Analytics	• Demand forecasting • Planning • Prediction • Process automation • Digital manufacturing	Risk management Visibility	Some disruptions can be avoided due to increased support to disruption decision making and recovery. Demand shocks can be better detected. Disruptions can be better anticipated (early warning). The impact of the disruption can be better assessed. Also, recovery after a pandemic caused disruption can be strengthened because of improved demand re-planning capability	Agrawal et al. (2020); Alicke et al. (2020); Belhadi et al. (2020); Cahn (2020); Council and Uberti (2020); DeAngelis (2020); George et al. (2020); Kilpatrick and Barter (2020); Kumar et al. (2020); Laluyaux (2020); Lin and Lanng (2020); Queiroz et al. (2020); Raghu (2020); Sharma A et al. (2020a, 2020b); Zhu et al. (2020)

Table 4 (continued)

Technologies	Applications	Findings		Sources
		Effect of technology	**Impact on another potential pandemic**	
Digital Supply Networks	• A digital twin of the entire supply chain • Digital twins of warehouses	Risk management Collaboration Visibility	Some disruptions can be avoided by the integration of all supply chain members in a model of the supply chain. This facilitated collaboration and increased visibility that can enable better avoidance of pandemic caused disruptions and improved responses to them once they have occurred	Agrawal et al. (2020); Cahn (2020); Hassoun and Mawet (2020); Ivanov (2020); Kilpatrick and Barter (2020); Kumar et al. (2020); Queiroz et al. (2020); Zhu et al. (2020); Sharma et al. (2020a)

7 Discussion

Based on our extensive review of the literature concerned with the COVID-19 events implications for supply chains and supply chain management, we present and discuss our findings in four main areas: the impact of the disruptions caused by COVID-19; the supply chain lessons from the COVID-19-related disruptions; the suggested supply chain resilience-driven solutions and how digital technologies are proposed as part of resilience-driven solutions to the future operations of global supply chains.

First, and concerning the impact of the event, our literature analysis found that multiple layers of the supply chain were impacted. Specifically, the analysis identified five major types of impact: *manufacturing, supply, sales, logistics* and *people*. That all these types of impacts were found to emanate from the same event, highlights the magnitude and complexity of the disruptions that followed the COVID-19 event. Not only did the event unfold at different layers of the supply chain, it also disrupted these layers simultaneously. This shows the severe challenges that many supply chains have been facing during the pandemic. As portrayed in Fig. 2, the analysis also found multiple interrelationships between the different types of impact, and one factor driving these interrelationships was the people impact dimension. In our analysis, we found that the pandemic is characterised uniquely by constraining people, their movement and their behaviour, as well as hindering or making the use of people as a resource highly unreliable (Strange 2020). Therefore, because people are involved in all stages of the supply chain, either as a customer/consumer, a manufacturing employee, a supplier or as a driver operating logistics systems, all stages of the supply chain were affected. Thus, the people dimension is a unique characteristic of the pandemic event and something previously largely overlooked in existing supply chain resilience research (e.g., George et al. 2020). The presented research adds new insights into the importance of people as a potential source and “epicentre” of supply chain disruptions.

Second, and because of the global and long duration of the COVID-19 event, it has spurred reflection as to the potential general systemic vulnerabilities in the way supply chains have been designed and managed. Thus, another finding from our analysis relates to the supply chain lessons from the COVID-19-related disruption. Six supply chain vulnerabilities are identified: overreliance on cost efficiency; globalized supply chains; lack of flexibility; lack of visibility; lack of preparedness for disruptions and interconnectivity of supply chains. Although each of these potential vulnerabilities individually has been identified and discussed previously (e.g., Pettit et al. 2013), the insight obtained from the COVID-19 crisis is new and different, as all identified vulnerabilities appear simultaneously and as a reflection of the same global disruption. This is new and seen as a unique configuration of vulnerabilities that can help us

characterise and reflect on, how globalised economy and trade in its present form is vulnerable when it meets a pandemic event like the COVID-19 crisis. Vulnerabilities can be thought of as unique and as latent to specific types of disruptions. The contribution of the present paper is to provide an overview of the set of vulnerabilities that the literature so far has found to be understood as related to the COVID-19 crisis, and thus more generally as relevant to pandemic-caused supply chain disruptions.

Third, and concerning how the literature portray the suggested supply chain resilience-driven solutions for the future operation of global supply chains, the literature analysis revealed that the most frequently proposes solutions are: Regionalization, redundancy, risk management, flexibility, visibility and collaboration. Based on these findings it is interesting to observe that actions related to two main types of response-strategies are proposed. The first, is buffering which attempt to "gain stability by establishing safeguards that protect a firm from disturbances that an exchange relationship confers" (Bode et al. 2011, p. 834). In our findings, we identified regionalization and redundancy as two of the most prominent examples of proposed buffering actions following the pandemic. The second type of response strategy suggested is bridging which attempts to "manage uncertainty through engaging in "boundary-spanning" and "boundary-shifting" actions with an exchange partner." (Bode et al. 2011, p. 834). In our findings we identified in particular collaboration and joint risk management as two of the most prominent examples of proposed bridging actions following the pandemic. Thus, our findings suggest that a diverse portfolio of response strategies is suggested by the literature. This is consistent with the magnitude and diverse impact of the supply chain disruptions that followed the COVID-19 event.

The final set of findings in the presented research is concerned with how digital technologies are proposed as part of resilience-driven solutions to the future operation of global supply chains. Based on our analysis, we see that the COVID-19 event has intensified the discussion of how digital technologies can enable resilience. The present paper contributes with new insights into this discussion. We complement, extend and operationalise the digitalization framework of supply chain risk management developed by Ivanov et al. (2019), by providing a comprehensive picture of the portfolio of technologies deemed relevant to pandemic disruptions. Our typology of relevant digital technologies as shown in Table 4 is new. By linking the individual technologies to their specific effects on resilience and their ability protect global supply chains from future pandemic disruptions, we extend existing research and provide important new insights to practitioners.

We summarise our findings in the model shown in Fig. 3. The model contributes to the existing body of literature by portraying the complexity of the COVID-19 event. It provides an overview of the preliminary supply chain lessons of

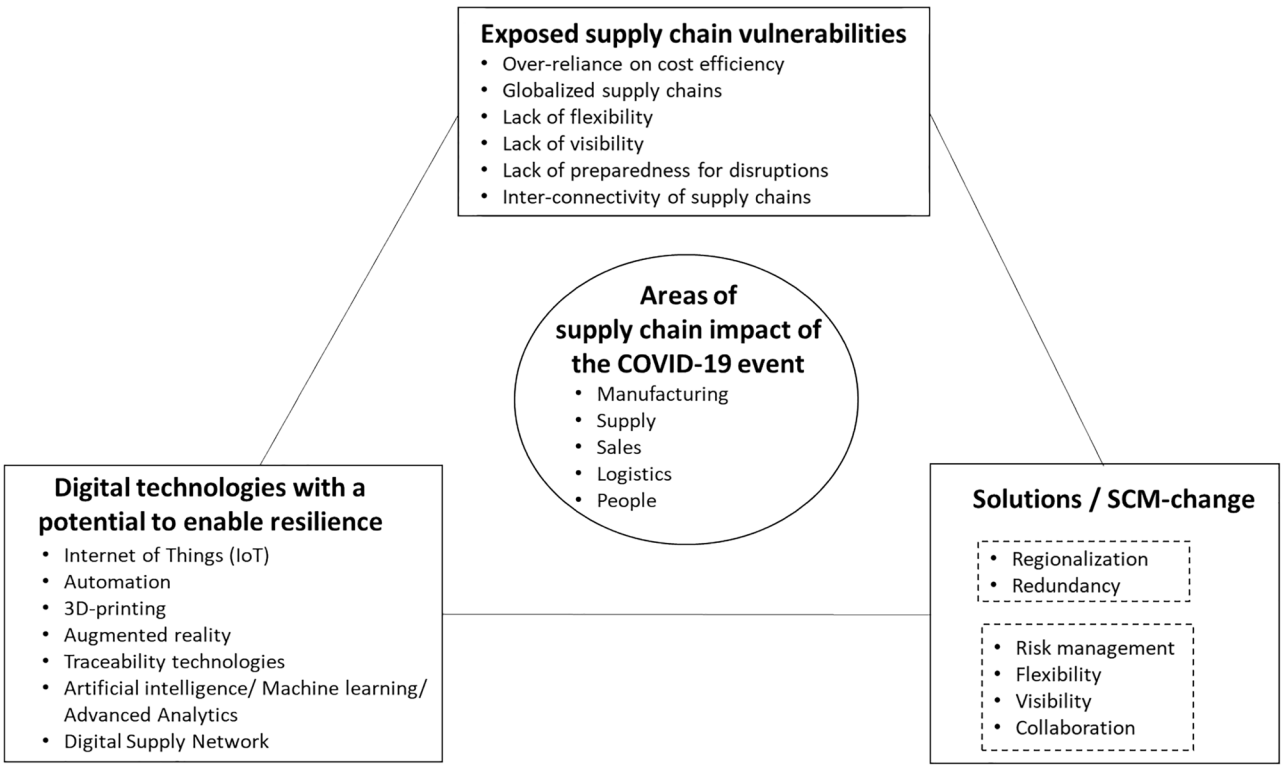

Fig. 3 The preliminary supply chain lessons of the COVID-19 pandemic disruption

the COVID-19 disruption. It further helps us understand the potential unique character of the pandemic disruption. Compared to other recently published reviews on the COVID-19 pandemic-related supply chain studies (Chowdhury et al. 2021), our focus is different, and our findings extend our collective knowledge about the event.

We focus, not only on synthesizing the impact of the event, but also on the learnings that have already taken place in the form of proposed response strategies. The present study further complements existing reviews, by also focusing on the proposed role of digital technologies in mitigating future pandemic disruptive events.

8 Final remarks

The structured literature review revealed several managerial implications and areas deserving of future exploration.

Concerning managers and practitioners working in the industry, the findings provide at least three levels of important insights. First, the literature synthesis provides managers with an opportunity to understand the complex nature of the multiple disruptions that followed the spread of the coronavirus in 2020. In particular, it highlights how a pandemic can affect supply chains in multiple and extraordinarily complex and interconnected ways across time and geographic locations. With this knowledge, managers should be better equipped to understand how a future pandemic can potentially disrupt their supply chain. Second, the literature synthesis provides insights into the general supply chain lessons stemming from the coronavirus crisis. Specifically, how and why existing practices have shown themselves incapable of sustaining supply chain operations during the COVID-19 pandemic. With this knowledge, managers are advised to explore the six identified vulnerabilities and to understand the extent to which these vulnerabilities apply to their supply chain. Moreover, managers are advised to set up an organisational structure and process that ensures that the lessons from the coronavirus pandemic that may be scattered throughout their supply chain are identified, collected, aggregated, and considered. Third, the presented research synthesized six proposed solutions (resilience capabilities) and seven technological clusters that are suggested to enable supply chain resilience to the current as well as to future pandemic disruptions. This list should be a valuable starting point for managers seeking to address future pandemic events and, thus, an opportunity for practitioners to address how supply chain resilience for such a disruption can be improved.

Concerning future research directions, it is important to note that the areas of supply chain resilience and supply chain risk management were two fairly well-developed areas of research long before the COVID-19 disruption (e.g., Fan and Stevenson 2018; Han et al. 2020). Although an elaboration of the knowledge within these areas is outside the scope of the present review, it should be noted that the COVID-19 incident is of magnitude and complexity, which makes it an interesting case to challenge the existing body of knowledge about disruptive events.

Based on the present literature synthesis, four areas deserving future exploration can be identified. First, how were the disruptions caused by COVID-19 interrelated in a complex system? How did time delays and the geographical relocation of the virus in waves play a role? More research is also needed to understand the people aspect of the coronavirus incident. Most of the articles in the review sample did not pay special attention to the people aspect of the disruption, except for Strange (2020) and George et al. (2020). This paper provides an overview of the people-related effects of the pandemic outbreak and notes the necessity for further research on the topic. Second, how did the COVID-19 incident challenge existing supply chain structures and practices, and how did it make supply chain managers reflect on and learn about their inadequate practices? Although the research presented in this paper contributes by mapping the reflections that emerged in the immediate aftermath of the coronavirus incident, future research should seek to understand how supply chains will reflect on this disruptive event and develop their lessons and conclusions. By exploring these practices, more general knowledge can be built on how supply chains learn as systems under extreme conditions. Third, the paper contributes by identifying six resilience capabilities and seven technology clusters and the corresponding applications that are proposed as particularly useful in addressing pandemic disruptions. Future research should explore these in detail and how they are correlated. Fourth, following this paper's approach, future studies are urged to explore not only the impact of the disruption and how it can be mitigated but also how the impact of major disruptions (like the COVID-19 case) is taken into account by organisations, i.e., how it is related to learning and subsequent repair actions. The model developed in this paper should be helpful in this regard.

Like any other study, the presented research holds limitations. The study presented the current knowledge on the nature of the disruption caused by the coronavirus pandemic on supply chains (including literature until the end of December 31, 2020). Given the time delay in the publication process and the fact that the pandemic is still ongoing and the effects of the pandemic still linger in the economy, there are limitations in how comprehensive a picture of the ripple effect through the supply chain can be painted. Another limitation is related to the structured literature review method. The method is dependent on secondary data, and some of the nonacademic contributions included in the literature sample to better reflect current debates about this phenomenon can

potentially be challenged with the reliability and robustness of their claims. Nevertheless, their claims are still interesting, as they help form the collective narrative on how supply chains should consider the COVID-19 case in their future practices.

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