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S.I. : DESIGN AND MANAGEMENT OF HUMANITARIAN SUPPLY CHAINS

Supply chain disruptions and resilience: a major review and future research agenda

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Abstract

Our study examines the literature that has been published in important journals on supply chain disruptions, a topic that has emerged the last 20 years, with an emphasis in the latest developments in the field. Based on a review process important studies have been identified and analyzed. The content analysis of these studies synthesized existing information about the types of disruptions, their impact on supply chains, resilience methods in supply chain design and recovery strategies proposed by the studies supported by cost–benefit analysis. Our review also examines the most popular modeling approaches on the topic with indicative examples and the IT tools that enhance resilience and reduce disruption risks. Finally, a detailed future research agenda is formed about SC disruptions, which identifies the research gaps yet to be addressed. The aim of this study is to amalgamate knowledge on supply chain disruptions which constitutes an important and timely as the frequency and impact of disruptions increase. The study summarizes and builds upon the knowledge of other well-cited reviews and surveys in this research area.

Keywords Supply chain · Disruptions · Review · Resilience · Ripple effect · Modeling techniques · IT tools

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1 Introduction

Driven by the globalization of markets and the competitive business environment, lean supply chain management (SCM) practices have become very popular (Blackhurst et al. 2005) calling for continuous flow processing with low inventory volumes, levelled and just-in-time production and accurate scheduling of transport for cross-docking operations leading to more cost-effective and responsive supply chains (SCs). Furthermore, the pressure for cost reductions has led to the outsourcing and offshoring of many manufacturing and R&D activities, especially the sourcing from low-cost countries. These trends place enormous pressure for undistracted operations and stable environments, but also increase their vulnerability to disruptions which consequently increases the operational and financial impact of supply chain (SC) disruptions (Zsidisin et al. 2005). Given that more than 56% of companies globally suffer a SC disruption annually, firms have started taking SC disruptions more seriously (BCI-Business Continuity Institute 2019). Therefore, the need for designing resilient SCs and preparing contingency plans is of paramount importance.

Supply chain disruptions may occur due to climate change or human factors. Based on the site of the National Oceanic and Atmospheric Administration (NOAA), which keeps a record regarding the number of disasters and their associated costs in the U.S, there have been 212 disasters since 1980 resulting in approximately $1.2 trillion in damage. A typical year in the 1980s experienced, on average, 2.7 such disasters in the U.S, 4.6 in the 1990s, 5.4 in the 2000s, and 10.5 in the 2010s. The occurrence of costly disasters has mounted. The same phenomenon is observed globally based on the OFDA/CRED International Disaster Database with less than 200 disasters per year in the 1980s and over 300 in the 2010s. Natural disasters like the Thailand flood and Japan's earthquake and tsunami in 2011 immediately affected the SCs of several products from firms such as Apple, Toshiba, General Motors, Nissan Motor and Toyota Motor causing negative results in these companies' reputations and earnings (Chongvilaivan 2011). Statistics show that about 40–60% of small businesses never reopen following a disaster (FEMA 2015).

On the other hand, recent examples of human factor disruptions include the tariffs imposed on billions of products for US importers in 2018–19, specifically to steel and aluminum, which led to import delays due to an inability of companies to adjust their current customs clearance programs and absorb the extra cost. This left a negative impact on the relations of the US with China, whose companies have been affected the most. Moreover, the wake of Brexit at the beginning of 2020 increases production failure risks to just-in-time auto manufacturers and others with similar operations (Banker 2019). The civil war in Syria has created humanitarian logistics problems with refugees' flows in Turkey and EU which based on the situation had to change supply chain strategies from serving populations on the move to serving dispersed but static groups of people, by supplying refugee camps, etc. (Dubey et al. 2019a, b, c). Recently, the deadly coronavirus outbreak in a major industrial and transport hub of central China has triggered lockdowns in Chinese (and many other) cities and factories which have severely restricted production and transport routes globally (Araz et al. 2020).

The issue of SC disruptions has been greatly emphasized in the literature. It is a topic that increasingly challenges the SC of products and their focal firms, as SCs have become very complex and interdependent and disruptions create a snowball effect with serious consequences to all related SC echelons. This propagation, the ripple effect as is denoted in the literature (Ivanov et al. 2014a, b) amplifies the impact of disruptions.

Although companies have high awareness about SC risks, more than 80% have been concerned about SC resilience (Marchese and Paramasivam 2013; Wright 2013), about 60% believe they have not yet developed and applied effective SC risk management practices (Sáenz and Revilla 2014). Therefore, managing risk in SCs is an important topic of supply chain management and has been the focus of research through reviews (Ho et al. 2015; Kleindorfer and Saad 2005), case studies (Ferreira et al. 2018) and an analysis of management models (Tomlin 2006). Related studies have exhibited a rich academic structure that encourages research in the field by identifying SC risks' types, ways to detect and assess them and apply the right methods to react to them by linking theory with strategy and managerial practices (Nakano and Lau 2020).

However, there is evidence of a shift away from traditional risk management thinking as a reactive tactic to disruptions and towards more proactive strategies such as building SC resilience which increases the chances of achieving business continuity in turbulent cases (Christopher and Peck 2004). Building resilience is a capability that enables the SC to anticipate, adapt and promptly respond to unpredictable events (Blackhurst et al. 2005), and therefore greatly appeals to the firms. However, its effective application requires the development of certain operational capabilities aligned across the SC partners (Ali et al. 2017).

Supply chain disruptions and resilience have developed to become a well-defined research area, exhibiting a rich academic output. Indicative are the special issues in prestigious journals such as in the Supply Chain Management: An International Journal in 2019 on "New Supply Chain Models: Disruptive Supply Chain Strategies for 2030" (Wilding and Wagner 2019) and in the International Journal of Production Research (IJPR) in 2016 on "supply chain dynamics, control and disruption management" (Ivanov et al. 2016a, b). Among the publications, numerous theoretical developments as well as review studies can be found exploring certain aspects of SC disruptions. There are also a few scientometric studies investigating mitigation methods (Bier et al. 2019), methods for building resilience (Centobelli et al. 2019; Hosseini et al. 2019a) and the connection between SC risk and artificial intelligence (Baryannis et al. 2019a, b).

From an academic standpoint, it is significant to classify and synthesize the output of research in a specific field, so that those interested can follow the field's developments and trends (Merigó and Yang 2017). Bibliometrics is one method of conducting such a classification, which guides academics toward a discipline's most influential studies (Gaviria-Marin et al. 2019; Godin 2006). On the other hand, the synthesis of knowledge can be performed through review and content analysis methods for classifying research and presenting a more analytical view of the developments of the field.

Our study examines the literature published in important journals on SC disruptions and resilience, a topic that has emerged the last 20 years, with an emphasis in the latest developments in the field.

The methodology is comprised of a profiling of our article pool, which is followed by a thorough review of advances in the field, completed by combining knowledge and providing information about supply chain disruptions, their impact and remedies, with a special focus on the ripple effect reduction, through the analysis of state of the art literature and comparisons. Finally, a review of the related technology advances draws a picture for the future of supply chain management against disruptions and provides a list of research ideas to gain a further understanding of the phenomenon, helping to better develop the field and prepare firms. Through this process managerial insights are offered for decision makers in the industry. Therefore, the manuscript aims to address: (1) how the literature has helped to advance theoretical debates and influence decision-making and (2) how the future is shaped, what the research gaps are that published papers have not yet addressed and constitute the future research agenda on SC disruptions. The study's contribution is to complement prior research and provide a broad picture of SC disruptions and remedies at a time when the existing literature has matured, the interest of firms on the topic has mounted, especially due to the COVID19 pandemic lockdowns, and there are new ways emerging that require further investigation.

The remainder of the paper is organized as follows. The second section discusses the study's methodology. The third section presents the profile of research on SC disruptions with an emphasis on the most influential papers. The findings from the content analysis of the related papers are described in the fourth section under eight subsections, focusing on the types of disruptive events, SC propagation-ripple effect, the impact of SC disruptions, resilience methods and recovery strategies, modeling approaches for SC disruptions, cost–benefit analysis of SC resilience, popular IT tools for resilience and response to disruptions and finishing with a future research agenda. The last section on discussion presents the research and managerial implications of this study.

2 Methodology

The paper's main research methodology follows a step by step review approach by using explicit methods and adopts a bibliometric technique to identify research streams in the analyzed literature and also a content analysis method to provide a description of research evidence.

The data collection process of the relevant articles on SC disruptions is described below. The Web of Science (WoS) database was queried for articles and reviews written in English that were published between the years of t and 2019 inclusive and contain in their title the terms "supply chain*" AND in the topic (title, abstract or keywords) the term disrupt* (*with its derivatives). The search identified 951 studies, which were analyzed based on their profile. Figure 1 presents a detailed schema of the methodology which is divided in three stages: preparation of dataset, profiling and content analysis and paper writing. The tools of the WoS database were utilized to derive profiling results such as the distribution of papers per year, the journals and affiliations with the most published papers and the citation report. The content analysis was completed with the help of EndNote capabilities

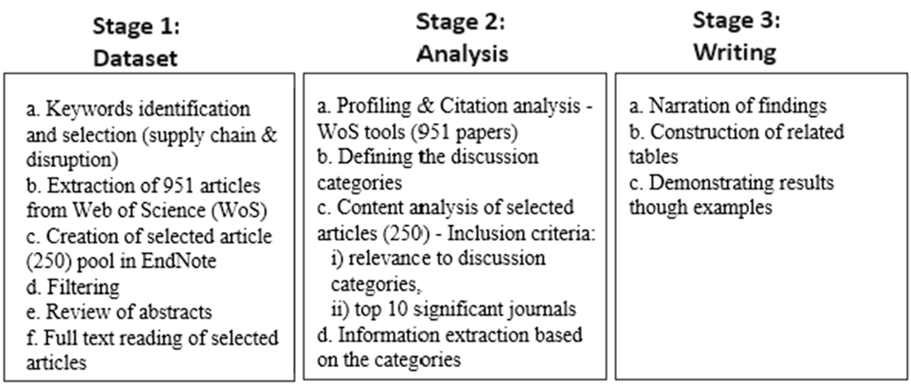

Fig. 1 Methodology schema

and two of the authors reading a selection of the articles. The criteria for an article's participation in the content analysis was based on the thematic area under investigation. A positive inclination was towards papers belonging to the top 10 journals that publish relevant subjects or towards highly cited papers (based on total citation or average citations per year). Around 250 papers were read in full and a number of them sketched the content of the specific categories. The content analysis categories include the types of disruptions (hierarchized by reason and frequency of occurrence), the impact that SC disruptions create (e.g. ripple-snowball effect), resilience, response and recovery methods, cost–benefit analysis of responses to disruptions, the most popular modeling approaches for applying resilience and mitigation strategies (topped with indicative examples and a special focus on the ripple effect), the IT tools and technological trends that enhance resilience and response to disruptions and research gaps that require further investigation. For this last section of future research, we also included ideas from 5 studies published in 2020 which cover issues related to the enormous SC disruption caused by the COVID19 pandemic.

3 Profiling research on SC disruptions

A look into the yearly distribution of the 951 related articles shows that the first papers on the topic were published as recently as in 2004, followed by continuous interest after that year. After 2015 there is a dramatic annual increase in the number of papers in the subject by around 30% from year to year. Around 30% of these papers are published in the following 10 journals: International Journal of Production Research, International Journal of Production Economics, Supply Chain Management: An International Journal, International Journal of Logistics Management, International Journal of Physical Distribution and Logistics Management, Omega: International Journal of Management Science, Transportation Research Part E Logistics and Transportation Review, European Journal of Operational Research, Computers & Industrial Engineering, and Annals of Operations Research. A lot of the work in the subject is conducted in the Russian Academy of Sciences, the University of Tehran and the Berlin School of Economics and Law.

3.1 Most influential papers and their contribution

If we assume that citation reports indicate the most read and referenced papers in the field, the most popular paper in the subject as of March 2020, is a framework for classifying SC risk management literature (Tang 2006), followed by one discussing SC disruptions in particular (Kleindorfer and Saad 2005).

Overall, the analysis of the 10 most important papers' contribution (Appendix Table 3) indicate that in their great majority are a) review papers about: (1) managing SC risks [either through a conceptual framework (Tang 2006) or as a textbook style (Chopra and Sodhi 2004) or a citation-review analysis (Tang and Musa 2011)], (2) managing SC disruptions (Kleindorfer and Saad 2005), (3) explaining SC resilience (Ponomarov and Holcomb 2009) and (b) survey papers discussing about: (1) the different levels of severity of SC disruptions through interviews (Craighead et al. 2007), (2) the impact of disruptions' announcements to the firms' stock price performance (Hendricks and Singhal 2005), (3) the perceptions of SC professionals of how SC agility is achieved (Braunscheidel and Suresh 2009) and (4) of their approaches to risk in global SCs (Manuj and Mentzer 2008). There is also one paper in this list which presents an inventory optimization model to assess sourcing strategies under disruptions (Tomlin 2006). Almost all of these papers have been published before 2010 (only one in 2011). Therefore, apart from their important content, the time that have been available is also a crucial parameter of their popularity.

A further investigation on trending WoS papers* (10 more recent papers with increasing citations - Appendix Table 4) revealed a focus on the digitalization of SCs and its impact on SC risk control, such as the effect of digital technology and Industry 4.0 on SC disruptions (Ivanov et al. 2019), the effect of the use of blockchain (Saberi et al. 2019) and employees' perceptions in using it (Queiroz and Wamba 2019). Altogether these 10 studies constitute a collection of (1) reviews about quantitative methods for modelling SC disruptions and aiding decision-making (Dolgui et al. 2018; Heckmann et al. 2015; Ho et al. 2015; Hosseini et al. 2019a; Snyder et al. 2016)], (2) conceptual frameworks of certain approaches on the subject (Ivanov and Dolgui 2019) and (3) surveys of professionals' knowledge on SC disruptions and adoption of mitigation tactics (Queiroz and Wamba 2019; Sodhi et al. 2012).

4 Content analysis results

In this section, a review of the selected studies is presented. The review is organized under the following areas: types and reasons of disruptions, the ripple effect, impact analysis of SC disruptions, resilience-response-recovery strategies to disruptions, popular quantitative approaches for the analysis of SC disruptions, cost–benefit analysis of resilience Vs disruptions, IT tools for enhanced resilience and research gaps for future research directions. All the subsections' information is generated through a content analysis of the important papers of our dataset that is enhanced with other external sources when necessary. Many sections are supported by tables that provide an account of the reported analysis.

4.1 Types of disruptive events

There is a vast literature which names and analyses the reasons for disruptions in SCs. Selectively, some of the most relevant studies are the following: (Baryannis et al. 2019a, b; Chopra and Sodhi 2014; Christopher and Peck 2004; Dolgui et al. 2018; Ivanov 2017; Ivanov et al. 2014a, b; Rao and Goldsby 2009; Tang and Tomlin 2008; Thun and Hoenig 2011; Vilko and Hallikas 2012; Zsidisin et al. 2016) which reveal the main reasons for the disruptions' occurrence. There are also a number of annual surveys on SC disruptions and resilience which are triggered by the Business Continuity Institute (BCI-Business Continuity Institute 2019) and other older surveys from Hendricks and Singhal (2005, Hendricks et al. (2009).

The literature provides several ways of grouping the reasons for disruptions/glitches:

(1) Based on the SC echelons are clustered under (a) production, (b) supply and (c) transportation disruptions (Ivanov et al. 2017);
(2) Based on the reason that caused the disruption, form 9 groups: (a) disasters (e.g. natural disasters, terrorism, war, etc.), (b) delays (e.g. inflexibility of supply source), (c) systems (e.g. information infrastructure breakdown), (d) forecast (e.g. inaccurate forecast, bullwhip effect, etc.), (d) intellectual property (e.g. vertical integration), (e) procurement (e.g. exchange rate risk), (f) receivables (e.g. number of customers), (g) inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.) and (h) capacity (e.g. cost of capacity) (Chopra and Sodhi 2014);

(3) Based on their frequency of occurrence, SC risks that occur regularly are: supply risks, process risks, demand risks, intellectual property risks, behavioral risks, and political/social risks (Tang and Tomlin 2008);
(4) Based on their nature and their source are classified under 5 categories: (a) process risk, (b) control risk, (c) demand risk, (d) supply risk and (e) environmental risk (Christopher and Peck 2004);
(5) Based on who they affect, from broad to specific, disruptions are: (a) external to the SC network and are termed environmental, (b) internal to the SC network but external to the focal firm, called network or industry risks (c) internal to the firm, called organizational disruptions, (d) problem-specific and (e) decision-maker specific (Rao and Goldsby 2009).

Moreover, disruptive events are characterized by their type, intensity, duration (Dolgui et al. 2019), source and impact. Below we provide examples from the literature based on these characterizations.

The disruptive events may have an individual impact (e.g. affect only one supplier, e.g. equipment breakdown, fire etc.), a local impact for suppliers in a geographic area (e.g. labor strike triggered by new worker's legislation of a State, etc.) or a global impact that affects all suppliers or SC echelons simultaneously. Such global events may include an economic crisis, a widespread labor strike in a transportation sector, etc. Suppliers may suffer all three types (individual, local, global) of disruption risks (Sawik 2014).

Natural disasters and catastrophic events are considered to have low probability, but are high impact events with significant consequences to the SC network. On the other hand, high probability and moderate impact disruptions are: unanticipated demand, rush orders, shortage in supply, company buyouts, delivery coordination and sourcing constraints (Scheibe and Blackhurst 2018). 589 professionals who participated in a survey in 2011 indicated that delivery chain disruptions were higher in their organizations than most other risks, but with less than average impact (Thun and Hoenig 2011). Aligned with the latter, the results of a Finish survey identified time delays (as opposed to financial and quality risks) as the most serious in terms of likelihood of occurrence (Vilko and Hallikas 2012). Earlier, Hendricks and Singhal (2003) reported that of the 14 primary SC disruption categories that were identified, parts shortages was by far the most frequent reported cause, and delivery disruptions was one of the leading causes of parts shortages. Another survey showed that infrastructural events are the cause of more than half of the disruptions (Zsidisin et al. 2016). The latest reports show that SC disruptions, such as cyber-attack, data breach and loss of talent/skills have become more evident since 2014. Consistently high rated causes of disruption in the 2010s include unplanned IT and telecommunication outages, as well as adverse weather, transport network disruption and outsourcer failure which have rarely dropped from the top five causes (BCI-Business Continuity Institute 2019).

Synthesizing the analysis of the individual papers referring to the types of disruptions, and survey papers and reports that have estimated their frequency of occurrence, in Table 1 we provide a summary of disruptive event categories, hierarchized by frequency of occurrence, from low to high. We also provide indicative references from our review database which refer to the specific category's events.

Table 1 Reasons for supply chain disruptions from low to high frequency of occurrence

Categories	Indicative Ref.
Catastrophic events/Macro level risks	Gunessee et al. (2018), Ivanov (2020a), Sheffi (2001)
Natural disasters (e.g. earthquake, flood, strong wing, fire, hurricanes, tsunami)	
International terror attacks (e.g. 2005 London or 2004 Madrid terror attacks)	
Political instability, mass killing, war, civil unrest or other sociopolitical crises, economic crisis	
Diseases or epidemics (e.g. SARS, Foot and Mouth Disease)	
Environmental incident (e.g. pollution, waste management)	
Legal, regulatory, labor, financial and bureaucratic events	Dwivedi et al. (2018), Elzarka (2013), Griffith et al. (2019)
New laws, rules or regulations (e.g. new tariff rates)	
Political factors and administrative barriers for the set-up or operation of supply chains (e.g. authorization from governments for oil extraction)	
Currency exchange rate volatility	
Human resource related events (e.g. Loss of talent/skills, illness, health & safety incidents)	
Business ethics incidents (e.g. human rights, corruption, Intellectual Property violation)	
Lack of credit, insolvency in the SC	
Demand-side events	Baghalian et al. (2013), Lee et al. (1997), Yang and Fan (2016)
Unanticipated or highly volatile customer demand, rush orders	
Insufficient or distorted information from customers about orders or demand quantities, delivery, coordination and sourcing constraints (bullwhip effect)	
Supply-side events	Atadeniz and Sridharan (2019), Ni et al. (2016), Sarkar and Kumar (2015)
Supplier/Outsourcer failure (e.g. bankruptcy, company buyouts, deliberate sabotage)	
Supplier product quality problems (e.g. product recall, rejected parts)	
Sourcing constraints (dependability, energy – natural resources scarcity, insufficient supplier capacity)	
Logistics–Transportation events	Dupont et al. (2018), Fan et al. (2017) Maiyar and Thakkar (2019)
Poor logistics performance of suppliers (delivery delay, order fill capacity, parts misplaced in the plant, poor delivery coordination)	
Poor logistics performance of logistics service providers (LSP) (scheduling errors, mislabeled parts, non-optimal transport route selection)	
Transport network disruption (caused by traffic, weather, customs delays, demonstrations)	
Equipment failures (truck, railroad, ship, port cargo-handling, and rail yard)	
Customs clearance, permit, and inspection delays at borders	

Table 1 (continued)

Categories	Indicative Ref.
Production-Infrastructural events	Ghadge et al. (2019), Khakzad (2015), Yang et al. (2017)
Loss of own production capacity due to technical reasons (e.g. equipment breakdown, IT infrastructure failure, machine deterioration)	
Unplanned IT or telecommunications outage	
Downtime or loss of own production capacity due to local disruptions (e.g. labor strike, fire, explosion, industrial accidents, gas leakage)	
Cyber-attack and data breach	

4.2 Supply chain propagation and the ripple effect

Given the geographical diversification, the number of tiers and the nature of product failure in an echelon of the SC may not only be a local problem but a far-reaching one which affects many echelons of the SC, but most importantly the end-customer. Perturbations originating in a localized point have the potential to be passed onto subsequent tiers of a SC with possible amplification effects (Wu et al. 2007).

The most-known such SC amplification effect is the bullwhip effect, which is caused by changes in customer demand that can propagate through the SC, amplifying in magnitude as the change passes to adjacent tiers (Lee et al. 1997). However, the bullwhip effect only describes one type of demand-side disruption which is caused by order batching, promotions, shortage gaming and mainly from a lack of coordination among the SC tiers as well as the lack of information sharing and transparency. This is a problem that has been cured in recent years with the use of enterprise resource planning (ERP) software, cloud services and other online sharing means.

On the other hand, the amplification effect which is caused by any type of disruption in the SCs is called the ripple effect (Ivanov et al. 2014a, b; Liberatore et al. 2012). The ripple effect describes the disruption propagation in the SC, the resulting SC structural dynamics and the performance impact of this propagation (Sokolov et al. 2016). Disruptions may occur upstream from interruptions in the supply-side (supplier/production failure, product quality problems, resource constraints) or downstream originated from demand-side and legal, regulatory and financial unexpected changes in the markets. An upstream example is the case of a supplier that has produced some components with harmful properties for the environment, which are supplied to the next upstream tier and further to tier-one, where the component should be suspended and recalled, resulting in delays for the whole SC of the final product (Levner and Ptuskin 2018).

The ripple effect describes the SC amplification and propagation effects of unpleasant events in broader terms and its consequences which may be much more severe than these of the bullwhip effect (Ivanov et al. 2017). The disruption frequency is usually lower, but the performance impact is higher than this of the bullwhip effect (Dolgui et al. 2018). The ripple effect has also been regarded with the snowball effect (Swierczek 2016) and domino effect (Khakzad 2015), which have similar definitions. However, the term ripple effect has dominated the literature and in many papers has been related with low-frequency high-consequence chains of accidents (Ivanov et al. 2017). Often, the ripple effect has a tremendous impact on the whole supply chain's performance, its ability to deliver to the end-customer and ultimately to the financial survival of its network of companies (Ivanov et al. 2014a, b; Kamalahmadi and Mellat-Parast 2016).

4.3 The impact of SC disruptions

Companies find it difficult to measure the effects of supply-chain disruptions and empirical evidence remains limited (Wagner and Neshat 2012). However, there are a few surveys and case studies that have attempted to shed some light and quantify the impact of disruptions. Additionally, there is a list of notable large scale disruptive events and their consequences (Dolgui et al. 2018) which are often used in the literature as outstanding examples. Indicative is the plant fire (infrastructural event) of Philips microchip in 2000 in New Mexico which caused a shortage of chips in the market. The undelivered supplies resulted in $400 million lost sales for the cellphone producer Ericsson. Similarly, in 2011 the flood in Thailand and the earthquake-tsunami in Japan (catastrophic event), where many component manufacturers are concentrated, resulted in huge losses for these companies. This also affected the reputation, earnings and shareholder returns of several international industries such as Apple, Toshiba, General Motors, etc., as companies are increasingly dependent on the supply chains' business continuity (Chongvilaivan 2011). In 2016, a contact dispute (legal event) between Volkswagen and two of its parts suppliers caused a production halt in 6 of the carmaker's German plants. Around 28,000 workers were laid off or made part-time (Dolgui et al. 2018).

Therefore, taking also into account the ripple effect, it is understood that disruptions cause many negative consequences to the entire SC and the individual firms involved. The relevant literature analyses a number of these consequences. Also, the accumulated knowledge from surveys of the last decade show that loss of productivity is the number one consequence followed by increased working cost, impaired service, customer complaints, loss of revenue and damage to brand reputation (BCI-Business Continuity Institute 2019).

In broad terms, the effect of SC disruptions may include a sales decrease and cost increase (Ponomarov and Holcomb 2009), from which many companies never recover (Wagner and Neshat 2012).

Sales decreases occur due to failure to meet end-customer demand as a result of product unavailability, partially fulfilled orders in terms of quantity and late deliveries. These lead to customer complaints, damaged image and brand reputation and loss of customers. The financial consequences then follow with lower sales, loss of revenues and reduced market share.

On the other hand, higher costs may occur (a) due to the use of alternative transportation means for product deliveries, and higher administrative costs for dealing with backorders, (b) due to premium supplier contacts for ensuring delivery of the limited resources from alternative geographical areas and firms, (c) due to production rescheduling as a consequence of stockouts of certain resources, or worse (d) due to production shutdowns (e.g. fire) and hampered productivity (e.g. labor strike, slack times in manufacturing) and lower assets and capacity utilization (Jabbarzadeh et al. 2018). Extra costs may incur also e) due to penalties for breaching contracts and failure to meet legal or regulatory requirements (Wagner and Neshat 2012). Overall the decreasing sales and increasing costs ultimately lead to loss of profitability and a decrease in the company's value (Ivanov 2017). Table 2 presents this degradation process.

Table 2 SC disruptions impact

Impact	Categories			Outcome
	Operations	Marketing	Finance	
Sales decrease	Failure to meet end-customer demand as a result of product unavailability	Customer complaints	Lower sales	Profit Loss reduced stock price
	Partially fulfilled orders in terms of quantity	Damaged image and brand reputation	Loss of revenues	
	Late deliveries	Loss of customers	Reduced market share Reduced stock price	
	Logistics	Supplier contracts	Production	
Costs increase	Use of alternative transportation means for product deliveries Higher administrative costs for dealing with backorders	Premium supplier contacts for ensuring delivery of the limited resources from alternative geographical areas and firms Penalties for breaching contracts and failure to meet legal or regulatory requirements	Production rescheduling because of stockouts of certain resources Production shutdowns (e.g. fire) Hampered productivity (e.g. slack times) Lower assets and capacity utilization	

Empirical research has shown that SC disruptions cause on average of a 107% drop in profitability (operating income), bring about 7% lower sales growth and an 11% growth in costs (Hendricks and Singhal 2005).

Poor firm performance is one of the most acknowledged effects of disruptions, but its negative impact is not consistent across all types of risks (Wagner and Bode 2008). Empirical research has shown that if recovery is possible, it takes up to 50 trading days (e.g. restart production) (Knight and Pretty 1996) and lower performance is observed for a period of two years after disruptions (Hendricks and Singhal 2005). The non-recoverers suffer a net negative cumulative impact of almost 15% up to one year after the catastrophe. Moreover, the more frequent the occurrence of a disruption within a focal manufacturing firm, the more likely it is that plant performance, relative to its competitors, will diminish. Consequently the higher the frequency of supply disruptions, the lower the plant performance (Brandon-Jones et al. 2015).

Another major impact that has been extensively studied is the financial impact of disruptions. Empirical findings indicate that financial markets react more dramatically to catastrophic and restrictive regulatory events, factors that usually cannot be easily controlled or avoided by firms, as compared to supply-side reasons, where some of them may be controlled or mitigated by firms through process improvement and early identification (Zsidisin et al. 2005).

At first sight, these findings indicate that managers should prioritize actions for contingency plans and the mitigation of catastrophic and regulatory-related disruptions, as these seem to have the highest financial impact. Nevertheless, apart from the severity of events, another factor that managers should consider when prioritizing actions related to disruptions is the frequency of occurrence of these disruptions and their cumulative financial impact. Therefore, low-impact but frequently occurring disruptions, combined, may have a more severe impact on shareholder wealth than infrequent high-impact events. Consequently, it is not irrational for managers to prioritize actions that could mitigate low-impact, high-likelihood events and especially these, mainly supply-side disruptions, that could be prohibited through process improvements (Zsidisin et al. 2016), good scheduling, appropriate maintenance and training, balancing inventory and capacity across the SC, etc. It is also empirically supported that firms with more operational slack, more days of inventory (inventory on hand) and a smaller sales over assets ratio (unutilized capacity), experience a less negative stock market reaction when disruptions occur, as slack provides resources and the required flexibility to handle disruptions (Hendricks et al. 2009).

Nonetheless, comparative surveys (Hendricks and Singhal 2003; Zsidisin et al. 2016) show that disruptions have a less detrimental impact to firm financial performance than in the past. The investigation of the impact to the firms' stock price of SC glitches' announcements (> 500) showed a dramatic fall that has smoothed throughout the years. Specifically, the effect of a SC disruption announcement (resulting in a production or shipment delay) on shareholder value meant an average reduction of above 10% on the stock market in the 90s (Hendricks and Singhal 2003), which has reduced to 2% in the 2000s (Zsidisin et al. 2016) probably due to an increased awareness and mitigation actions regarding disruptions and fast recovery (Wagner and Neshat 2012). Albeit the considerable advancements that have been achieved, disruptions now occur in greater frequency and intensity, therefore the consequences are still, in many cases, dramatic (Wagner and Neshat 2012). Realizing this negative impact, businesses are recognizing the importance and are attempting to create and be part of more resilient SCs (Jabbarzadeh et al. 2018).

4.4 Resilience methods and recovery strategies

To successfully recover from a SC disruption, a firm needs to activate effective methods (Blackhurst et al. 2005). According to the literature, managers need to respond to such incidents by following three identified stages of response: first detecting the volume of disruption, then designing or selecting a predesigned recovery method to tackle the disruption and finally deploying the solution (Chopra and Sodhi 2014). Several literature reviews have described the stages, methods and techniques of firm reaction and recovery after a disruption (Dolgui et al. 2018; DuHadway et al. 2019; Ivanov 2020b; Ivanov et al. 2017; Sawik 2019).

According to the literature (Chowdhury and Quaddus 2017; Dolgui et al. 2018) resistance (proactive approach) and recovery (reactive approach) are included in the resilience concept. A firm needs to maintain redundancy (high safety-stock, additional production capacity) and flexibility (alternative suppliers for sourcing, alternative transportation depots and modes for delivery) to resist against disruptions and use them effectively to reduce their impact. Likewise, the recovery stage incorporates some of the same tactics as the resistance approach, such as the use of backup suppliers for sourcing, the use of the buffer stock for satisfying customer orders and redundant capacity for continuing the production (Ivanov et al. 2017).

Other important mitigation strategies for disruptive events focus on better demand forecasting (Scheibe and Blackhurst 2018), better coordination amongst the SC echelons before and after the disruption with the use of information-sharing (Dubey et al. 2019abc), joint relationship efforts, and decision synchronization (Nakano and Lau 2020) by deploying supply chain management software (such as warehouse and transport management systems and vendor managed inventories) connected to the ERP and business intelligence software add-ons (Brusset and Teller 2017).

However, surveys show that firms address disruptions most commonly with increased safety-stock, dual or multi-sourcing, and better forecasting. Although they consider coordination between the SC nodes very significant to recover from disruptions, in reality they act in isolation and their visibility of the SC extends only to one tier above and one tier below (Scheibe and Blackhurst 2018). Low collaboration and responsiveness has emerged as a great vulnerability (Pettit et al. 2013). Real-time supply-chain reconfiguration software could enhance responsiveness against specific situations (Blackhurst et al. 2005) and improve coordination and decision-making by recomputing, for example, optimal routes and facility selection to maximize demand fulfillment and minimize penalties and delay costs due to the disruption (Banomyong et al. 2019).

A representative example of the backup sourcing recovery option is the incident concerning the fire at the Philips microchip plant in Albuquerque. Ericson experienced a production shutdown because its materials were sourced only from that plant while Nokia took advantage of its emergency backup sourcing strategy to obtain chips from other suppliers (Chen and Yang 2014). A resilient design of a SC that promotes flexibility is described through the BASF example. BASF built a resilient SC with safety and risk prevention measures that included globally valid guidelines and requirements for capacity and security trainings for staff. In 2016 a pipeline at BASF facility in Germany exploded and destroyed a terminal for the supply of raw materials, limiting the access to key raw materials and product inventories. During this time, logistics was temporarily shifted from ships and pipelines to trucks and trains. BASF was prepared for an incident and was in close contact with its customers to keep them informed about the current availability of products to minimize the impact on customer deliveries, which resulted in smaller than expected economic consequences from the accident (Dolgui et al. 2018). Another example of flexibility importance is the case of the 2015 Nepal earthquake in which humanitarian organizations offering aid to locals were met with great disruptions (delays) in relief delivery. They identified the significance of developing a flexible network with the most influential factors being IT support, fleets' (re) scheduling, and relief packages' volume (Baharmand et al. 2019).

Firms belonging to specific SCs can utilize practical assessment tools from the literature that were developed to measure their own SC resiliece (Chowdhury and Quaddus 2017; Pettit et al. 2013). This is a first step to ackowledge their readiness to resist and respond to disruptions and understand where they should make efforts to improve.

4.5 Popular modeling approaches

4.5.1 Modeling approaches for SC disruptions

Mitigation and recovery are very important procedures and the adoption of these "recovery strategies" include processes based on quantitative methods (Ivanov et al. 2014a, b), which usually evaluate the effectiveness of each strategy prior to its implementation. Quantitative analysis methods for anticipating operational and disruption SC risks mainly include mathematical optimization, simulation, and control theory to control risk, respond and stabilize the execution process in case of disruptions and to recover or minimize the middle-term and long-term impact of deviations (Ivanov et al. 2017). Mathematical optimization offers optimal solutions by using algorithmic models; simulations are models that provide the "what if' scenarios" and control theory provides additional analytical tools often used to analyze system dynamic performances over time (Yang and Fan 2016).

More specifically, optimization models offer analytical solutions which determine the impact of disruptions and identify resilient SC policies. Such models can incorporate a large variety of parameters and objectives (e.g. minimization of disruption cost). Mixed-integer programming (MIP) is a category of optimization problems that has been repeatedly used to model SC disruptions (Ivanov et al. 2017). However, a major limitation of optimization models is that they cannot capture the dynamic nature of SCs (e.g. disruptions are modeled as static events, without considering their duration or erratic impact) and therefore make a high number of assumptions (e.g. known demand, suppliers' reliability, etc.). On the other hand, stochastic programming modeling allows for the insertion of some uncertainty through probability distributions depicting disruption event scenarios and leads to optimal solutions by taking into account multiple objective functions (Sawik 2014). Stochastic programming models incorporate a set of discrete scenarios with a given probability of occurrence. The probability distributions may describe demand uncertainly, disruption impact uncertainly, costs uncertainty for applying response and recovery strategies, etc. Stochastic programming techniques have also been used to model disruptions in SC, however, the scenario-based approach of stochastic programming modelling exponentially increases the number of variables and constraints and makes these models difficult to implement and run.

Simulation methods are more flexible than stochastic optimization models as they are used to replicate system behavior and allow for a dynamic approach of randomness in disruption and recovery policies, as well as they incorporate and handle more complexity (more probabilistic scenarios for more variables simultaneously), incorporate the time dimension and even offer real-time analysis, and multiple results under each what-if scenario. Simulation can also be applied to enhance the optimization results or be used as a simulation-based optimization technique. Simulation techniques such as discrete-event simulation, system dynamics, agent-based modeling, optimization-based simulation and graph theory-based simulation have been applied to describe and model the impact of the ripple effect in SC disruptions (Ivanov et al. 2017) among other things.

Control theory has also the analytical ability to execute SCs over time and is used to analyze eventual system dynamic performances. The development of control models is usually related to specific operational risks which constitute the key control metrics (such as, demand fluctuation, degree of information sharing, speed of convergence) for quantifying disruption recovery performance (Ivanov and Sokolov 2019; Yang and Fan 2016).

Another technique which is apparent in the analysis of SC disruptions is graph theory (e.g. Bayesian network, decision trees) which, through mathematical structures, describes the interrelationships of the SC and based on the predictions and decision scenarios model pairwise relations between entities (Hosseini and Ivanov 2019). Finally, game theory (e.g. Stackelberg game) is another type of mathematical modeling which focuses on the strategic interaction among rational decision-makers and, given the order of decisions from decision-makers, certain scenarios are deployed about their reactions in SC disruptions.

Needless to say, inventory theory is dominantly used for modeling SC disruptions. It incorporates popular inventory models (deterministic or stochastic optimization models), such as economic order quantity models and periodic review models which determine safety stock, optimal ordering and production quantities during the design of resilient SCs and the recovery period to minimize total costs, capturing the trade-offs between inventory policies and disruption risks. These models can be two-echelon or multi-echelon models based on the length of the SC.

In the examined articles, we have identified that most papers use optimization methods, followed by papers that apply simulation techniques. There are also studies that present statistical analysis of database data or survey, e.g. (Brusset and Teller 2017) or that use graph theory, e.g. (Nakatani et al. 2018) and game theory, e.g. (Fang and Shou 2015). From the optimization methods notable is the use of stochastic programing e.g. (Snoeck et al. 2019), mixed-integer programming, e.g. (Amini and Li 2011) and multi-objective programing e.g. (Teimuory et al. 2013). The simulation methods used are discrete-event simulation, e.g. (Ivanov et al. 2017), system dynamics, e.g. (Kochan et al. 2018) and agent-based modeling, e.g. (Hou et al. 2018). Looking into our article pool, the papers that have developed quantitative analysis methods model resilience, response and recovery strategies. (Appendix Table 5 shows 10 indicative papers as examples of the variety of quantitative methods used in the relevant literature with a brief explanation of the model's purpose.)

Quantitative techniques offer a great range of analysis which varies from solving single, simple problems to very complex and interrelated ones. The latter more precisely describes the need of SC modeling. Operations and supply chain managers can choose from the available quantitative tools for different application areas of SC disruptions and determine an optimal or near optimal solution.

4.5.2 Modeling approaches for the ripple effect

Special attention is given in the most recent literature (after 2014) with regards to the ripple effect and the ways to manage it/reduce it through tactics that are tested in quantitative models. From a search in the Web of Science database regarding the literature on the ripple effect of SCs (keywords: “ripple effect” and “supply chain”), 31 journal papers have been identified, 18 of which are published in the IJPR, 3 in the International Journal of Production Economics (IJPE) and the remaining 10 each in different journals. Prof Ivanov is the author in 21 of these, establishing the ripple-effect as a scientific topic in the area of SC disruption management, by using an analogy to computer science where ripple effect determines the disruption-based scope of changes in the system (Ivanov et al. 2014a, b).

A thorough analysis of the ripple effect in SCs is given in a review paper (Ivanov et al. 2014a, b) and its follow-up (Dolgui et al. 2018) which provides a framework for the reasons of the ripple effect (sourcing strategy, production planning, inventory management, and control), presents its quantitative modelling approaches (including mixed-integer programming, simulation, control theory, complexity and reliability theory) and provides an analytic count down of future research avenues. Adding to the latter an overview paper demonstrates the positive impact of technology (big data analytics, 3D printing, blockchain, etc.) on the ripple effect mitigation (Ivanov et al. 2019). Attention is also drawn to case studies. For example a highly cited paper published in IJPE (Koh et al. 2012), assesses impact of actions for greening the SC and the triggering of the ripple effect and another one based on the analysis of the 2009 Italian earthquake uses MIP to model protection plans of regional disruptions by identifying which facilities to protect first (Liberatore et al. 2012).

The majority of the remaining papers in the literature on ripple effect are focused on modelling the phenomenon, which requires the inclusiosn of many SC echelons and thus more complex processes in the model, and exploring mitigation tactics. This is done by the use of mathematical models e.g. (Hosseini and Ivanov 2019; Ivanov et al. 2015; Ivanov et al. 2013; Kinra et al. 2019; Pavlov et al. 2019; Sokolov et al. 2016) or by simulation techniques which are frequently used to present the ripple effect phenomenon (Dolgui et al. 2019; Hosseini et al. 2019b; Ivanov 2017; Ivanov et al. 2016a, b). (Appendix Table 6 gives an overview and a categorization of the main papers focusing on the phenonmenon and their contribution).

Research on papers that focus on the ripple effect is dominated by the performance analysis of disruptions probabilities, especially for supplier failure. There is an urge for studies to explore other characteristics too by applying new modelling approaches with real company data and visualization techniques (Dolgui et al. 2018; Kinra et al. 2019). Forward and backward propagation analysis with the use of Bayesian networks and inclusion of the dynamic recovery time and cost by applying multi-objective stochastic optimization and agent-based models are some of the approaches that can be tried out (Hosseini et al. 2019a).

4.6 Cost–benefit analysis of supply chain resilience

Since disruption implies serious commercial costs, the mechanisms for resilience, response and recovery are of vital importance to all SC echelons. An approach to reducing the costs of disturbance events is to highly motivate the managers to implement risk mitigation programs in the firm and engage in knowledge development activities (Cantor et al. 2014). Therefore, SCs should be protected in anticipation of disruptions by means of mitigation actions such as having safety stock, capacity reservations, backup sources and other methods, which nevertheless raise the level of management complexity and end-up being costly solutions themselves, especially if no disruption happens (Ivanov et al. 2019). So, resilient SC designs result in costly systems, which could negatively influence SC’s financial performance. To overcome the resulted costs, an efficient combination of resilient elements must be implemented, such as structural variety and complexity reduction, process and resource utilization flexibility and non-expensive parametric redundancy together with decision-support systems for SCs (Ivanov et al. 2019). Nevertheless, researchers have come to the conclusion that the cost for building resilience by using slack resources and visibility is smaller than the cost of SC disruptions (Jabbarzadeh et al. 2018).

Unfortunately, cost–benefit analysis (CBA) is not common in studies that present SC control models (Ivanov et al. 2019). The beneficial portion of the CBA can be modelled via the reduction of the disruption risk by a given percentage or its incurring costs, the shortening of the period of the disruption impact or via sustaining the service level (Namdar et al. 2018). On the other hand, although the cost of risk mitigation is considered visible (e.g. performance measures include fixed and variable costs, disruption costs, recovery cost), its accurate calculation is made difficult by the fact that recovery costs are generated by the adoption of a combination of proactive and reactive policies while cost analysis can also be extended to the operative losses and long-term future impact of deviation and recovery (Ivanov et al. 2017).

Nevertheless, there are many studies in the literature that, in their modeling approach, incorporate in the objective function the cost element and then by running what-if scenarios can measure the impact of certain policies and the overall benefit. For example, a study (Mori et al. 2014) developed a risk simulator for a multi-tier supply chain to evaluate the cost of retailer's decentralized ordering and the effect of risk mitigation, identifying the cost–benefit relationship. Another study used a MIP which enables what-if analyses of cost and performance trade-off options in the SC (Das and Lashkari 2015).

Therefore, the use of quantitative models are viable methods for testing ways of minimizing costs of disruptions and contributing to the responsiveness and flexibility of the entire SC. Another identified way is for companies to choose to invest in social responsibility in order to balance disruption costs and resilience planning. Even though investment in corporate social responsibility activities could bring more cost to the company, it is also capable of increasing profit and reducing risk by decreasing production inefficiencies and increasing sales, access to capital and new markets (Cruz 2009). In line with this, it is the firm's investment in good communication infrastructure, with the help of professionally qualified marketing agencies, that help problems with demand risks (e.g. demand decline) be mitigated (Diabat et al. 2012) or the implementation of pre-disaster/pre-disruption defense measures, such as insurance purchasing (Song and Du 2017). In any of these cases top management commitment is essential for building robust SC connectivity and information sharing systems to accomplish efficient SC integration (Shibin et al. 2017)

4.7 Popular IT tools for resilience and response to disruptions

Modeling methods paired together with digitization enabled the development of tools that have led to many interesting applications for aiding SCs in general and SC resilience and real-time response to disruptions in specific. Many papers in our database offer very interesting overviews of digital technologies and their impact in mitigating disruption risks in the SC.

Computerized planning systems tools, such as materials requirements planning, manufacturing resource planning and enterprise resource planning (ERP) were the first software to help with the scheduling of operations and timely rescheduling in the case of disruptions and the retrieval of enterprise data from a single access point for informed decision-making (Baryannis et al. 2019a, b), especially in cases of emergency interventions. Moreover, flexible manufacturing systems with sensors and advanced robots for more precise, reliable and easily adaptable production processes; automated guided vehicles and automated tracking and tracing technologies for safe, accurate and fast fulfillment of orders from wholesalers; radio frequency identification (RFID) for inventory control; geographic positioning systems (GPS) for timely and less costly distribution of goods are all technologies that have highly been adopted in the last decades and have greatly aided the SCs and reduced their response time, especially with their real-time capabilities for fast implementation of contingency plans (Blackhurst et al. 2005).

Then, the Internet of Things (IoT) have taken these technologies a step forward. The IOT is a dynamic network infrastructure with self-configuring capabilities of interoperable physical devices (Things), such as wireless sensors, smart devices, RFID chips, GPS, which can monitor, report and exchange data using intelligent interfaces seamlessly integrated into the information (Wi-Fi or data) network (Kranenburg 2008). The IOT can effectively track and authenticate products and shipments and inform on the location of goods, their storage condition and their time of arrival. Enhanced with augmented reality, which adds digital elements to a live view by using a camera, the IOT combines the real with the virtual world. A few examples of the uses of augmented reality in SCs are: the easier navigation of workers or tracing systems in the warehouse with the help of a graphic overlay of the space and its products, the reduction in the searching time of courier drivers for a box in the truck for the next delivery with a graphic overlay of the initial loading of products in the truck, informing the customers in real-time about prices and stock availability of items on the shelves by incorporating virtual labels viewable from smartphone cameras or google glasses. Like this, IoT and augmented reality technologies offer SC visibility and traceability, sending early warnings of internal and external disruptions that require attention, reducing uncertainty and enhancing effective internal operations and collaboration among all SC players (Ben-Daya, Hassini, & Bahroun, 2019).

Moreover, Industry 4.0, 3D printing, big data analytics (BDA), as well as blockchain also constitute tools of the new era that quickly find their way into the business world.

With the help of the IOT, Industry 4.0 is the smart factory of cyber-physical systems, like internet-connected workstations, conveyors and robotics, which autonomously control and monitor the route of products in the assembly line offering customized configuration (Katsaliaki and Mustafee 2019). Hence, Industry 4.0 enables the production of customized goods at the cost of mass production, with shorter lead times and better capacity utilization. Cost risks are minimized while higher market flexibility and responsiveness to customers is offered with customized products and risk diversification (Ivanov et al. 2019). On the other hand, 3D printing (additive manufacturing) builds a 3D object from a computer-aided design model by sequentially adding material layer by layer. This method of production, which progressively broadens the range of products it offers, constitutes a disruptive technology to the traditional SC configuration as products can be manufactured to SC echelons closer to the customer and even at the retailer's site. The shorter lead times and the reduction in demand risks as manufacturing comes closer to the customer are the main contributions made by this technology (Ivanov et al. 2019) to aid in the reduction of disruptions.

With recent revolutions in technology, data is generated much quicker from different sources and technologies are in place capable for their storage, categorization and analysis. Statistical analysis and reliability become stronger with the increased data volume and the high number of factors for analysis. Therefore, predictive methods have better explanatory power (Gunasekaran et al. 2016) and together with machine learning algorithms, artificial intelligence (AI) that allows computers to evolve behaviors based on empirical data (Chen and Zhang 2014) offer answers to demanding questions and what-if scenarios through prescriptive analytics. Big data analytics and machine learning methods came to the foreground as enablers of value creation from massive data, offering new competitive advantages to companies (Chen et al. 2012). They have increased SC data visibility and data transparency and can reduce information disruption risks and behavioral uncertainty as well as demand risks through predictability (Baryannis et al. 2019a, b; Brintrup et al. 2019); all of which are positively linked to SC resilience.

Blockchain technology is a distributed database of records or shared public/private ledgers of all digital events that have been executed and shared among participating blockchain agents (Crosby et al. 2016). Blockchains can be considered a disruptive technology for the general management of SCs, specifically in the field of suppliers' contracts. Distributed contract collaboration platforms using blockchain technology could guarantee the traceability and authenticity of information, along with smart contracts (computer protocols which digitally verify or enforce the agreed terms between the members of a contract without third parties' involvement). These transactions are trackable and irreversible and validate transactions (Saberi et al. 2019). This brings a new era in SCs and a remedy to fraudulent acts and security risks (Wang et al. 2019).

Especially for the ripple effect, information technology can have a very positive mitigation influence. RFID technology can offer feedback control and SC event management systems can communicate disruptions to the other SC tiers and assist in revising and adapting schedules. For example, Resilience360 at DHL is a cloud-based analytics platform for managing disruption risks by mapping end-to-end SC partners, building risk profiles, identifying critical hotspots in order to initiate mitigation actions and alert in near-real time mode about events that could possibly disrupt the SC (Dolgui et al. 2018).

4.8 Future research agenda

Following a content analysis of selective papers on SC disruptions, future directions have been identified which we hope will inspire new scholars to establish their research agenda in this field. The selection of the research topics was made primarily on the grounds of managerial applicability without diminishing the importance of theory advancements. The great majority of the papers include a shorter or longer future research section but, in many cases, this is targeted to the advancement of their modelling technique, of their data collection approach, or the hypothesis testing which are out of the scope of this study's agenda. Below we take a practical approach of the field and we try to map research on SC disruptions especially with regards to the use of new tools and resilience approaches. There is a list of 34 research directions organized in seven themes. These relate to research about (a) effective resilience strategies, (b) SC disruptions in specific sectors, (c) a special focus on human resources management (HRM) and behavioral analysis, (d) modelling approaches with an emphasis on the ripple effect, e) combination of modeling approaches with new information technologies (IT), f) research about the implementation of these new IT/digital technologies and g) research driven by the recent enormous disruptions due to the COVID19 pandemic. It is notable that about 1/3rd of these topics are related to the use of digital technologies which greatly enhance modeling capabilities and decision-making to tackle and resist SC disruptions. Each research direction begins with a short title in bold, depicting its aim and its methodology approach.

4.9 Resilience strategies

(1) *Resilience Strategies—Multi-method (modelling, survey)* Which strategy or combination of strategies: redundancy (excess inventory, spare capacity, multiple sourcing), flexibility (flexible production systems and distribution channels, multi-skilled workforce), collaborative planning (information-sharing, joint relationship efforts, decision synchronization), contingency planning (back-up suppliers-transportation modes) is most effective for building resilient SCs to disruption risks? (Centobelli et al. 2019)
(2) *Resilience Strategies—Survey, case study* Is it true that SCs that adopt a flexibility strategy utilize a higher degree of information sharing and collaboration through higher ICT utilization in comparison to adopting a redundant strategy? Is it true that redundant strategies are more expensive to implement (need more capital and operating cost) than flexibility strategies? (Nakano & Lau, 2020).
(3) *Resilience Strategies—Survey* What is the effect and relative importance of specific disruptions (such as, ineffective suppliers' management, lack of information sharing and risk assessment) so managers can prioritize the allocation of resources to tackle them? (Centobelli et al. 2019).
(4) *Risk metrics—Survey* What are the most effective, as opposed to the most used SC risk metrics (performance measurement system), among recovery time, safety stock, customer service level, total cost and others, for managers to focus on and under which circumstances (e.g. ripple effect)? (Dolgui et al. 2018).

4.10 Certain sectors of SC disruptions' application areas

(5) *Military—Mixed methods* Exploring effective disaster resilience approaches for the military (Centobelli et al. 2019).
(6) *Perishable products—Modelling* Modelling disruptions in the SC of perishable products and their limited resilience strategies as redundancy strategies may not be an option (freshness, write-offs) but others may be, such as customer segmentation by requirements for freshness and product batching (Dolgui et al. 2018).
(7) *Food—Mixed methods* Analysis of the use of the IoT and other recent technologies for preventing avoidable food waste generation, food safety and efficiency throughout the food SC (Ben-Daya et al. 2019).
(8) *Information Systems disruptions—Mixed methods* Research on disruptions in the information systems and the networked cloud-based digital SC environment (Dolgui et al. 2018).
(9) *Reverse logistics—Modelling* Studying the disruptions that take place in the reverse logistics flows of SCs (e.g. unavailability/limited space in the warehouse that stores the collected recyclable materials) for analyzing their impact to the overall SC performance and identifying effective response and mitigation strategies (Dolgui et al. 2018).
(10) *Humanitarian aid—Modelling* Analysis of the fair allocation of the limited resources in situations of severe regional disasters which usually simultaneously lead to humanitarian emergency and industrial crisis, in order to balance human life rescue, everyday life and the recovery of the industrial sector (Dolgui et al. 2018).

4.11 HRM

(11) *Behavioral analysis—Modelling* Employing agent-based simulation to model managerial decisions subject to individual risk perceptions, such as collaboration issues (trust and information sharing) and SC risk management culture (leadership and risk-averse behavior) (Dolgui et al. 2018).

(12) *Behavioral analysis—Mixed methods* Analysis of the patterns of human behavior when managers are faced with real data or the dashboards of big data and visualization/cognitive computing approaches (that their development mechanisms may or may not be trusted) and the nature of their governance and decision-making, especially when related decision refer to disasters causing humanitarian crises (de Oliveira and Handfield, 2019).

(13) *Training—Survey* Analyzing ways that offer successful training to company staff in the related departments to effectively cope with SC disruptions, which create a stressful environment and require preparedness (Dolgui et al. 2018).

4.12 Modelling methods about SC disruptions

(14) *Ripple effect—Multiple models* Modelling SC disruptions by considering the dynamic recovery time/cost. More modelling approaches are needed for capturing the disruption propagation and SC design survivability and for evaluating recovery policies and their implementation (Dolgui et al. 2018).

(15) *Ripple effect—Stochastic modelling* Development of two-stage stochastic models with the first-stage objective function to minimize the traditional SC cost (procurement, supplier evaluation, transportation costs) and the second-stage objective function to measure the SC resilience under all possible disruption scenarios (Hosseini et al. 2019a).

(16) *Ripple effect—Model validation* Practical validation of the simulation and optimization models for preventing and mitigating the ripple effect in the SC with real company data, such as coordinated contingency plans (Dolgui et al. 2018).

(17) *Ripple effect—Model visualization* Adding visualizing features to the simulation models of the ripple effect (Dolgui et al. 2018).

(18) *Ripple effect—Bayesian Networks* Forward and backward propagation analysis using Bayesian Networks (a unique capability of this method) by entering any number of disruption observations to analyze the ripple effect in complex supply networks with a large number of nodes and links (Hosseini et al. 2019a).

(19) *Resilience Vs Sustainability—Multi-objective stochastic optimization* Developing multi-objective stochastic optimization models capable of making trade-offs between resilience (that requires capacity buffer, surplus inventory, multiple sourcing) and sustainability decisions (which on the contrary requires less redundancy) (Hosseini et al. 2019a).

(20) *Large supply networks—Modelling Toolbox* Development of a common language to facilitate the development of reference models for supply networks with a standardized toolbox of supply network representations and identification of suitable methods for analyzing risks in complex supply networks (Bier et al. 2019) and will accelerate comprehension and execution.

4.13 Hybrid models combined with IT

(21) *Predicting SC disruptions—Prediction and machine learning algorithms* Development of prediction models and adaptation of SC disruptions management practices with the use of prediction algorithms and machine learning techniques such as unsupervised learning algorithms which can be used to mine SC data, identify patterns related to certain risks and be trained to recognize risk patterns and their incurring probability (Baryannis et al. 2019a, b).

(22) *Risk management practices—Mathematical programming, Multi agent systems, Semantic reasoning, Machine learning techniques and BDA* Development of hybrid models to analyze risk management practices by combining mathematical programming (effective in modelling highly complex systems for SC risk avoidance and mitigation), with agent-based approaches, BDA and machine learning techniques (capable of automated decision-making by creating automated rule-based reasoning and learning and handling of big and variable data) in order to select an appropriate response strategy (Baryannis et al. 2019a, b; Hosseini et al. 2019a).

(23) *Digital SC twin—Simulation, optimization and BDA* Analysis of the combination of simulation, optimization and data analytics to create a digital SC twin – a model that represents the state of the network in real-time (Ivanov et al. 2019) offering end-to-end SC visibility when all players are included. A disruption in a SC echelon can be reported by a risk data monitoring tool and transmitted to the simulation model. The simulation model in the digital twin can measure disruption propagation and impact, test recovery policies and adapt the contingency plans based on the situation (e.g. considering back-up routes on-the-spot) (Hosseini et al. 2019a; Ivanov et al. 2019).

(24) *IoT – Modelling* Modelling SC problems (procurement, production planning, inventory management, quality, maintenance) in an IoT environment. Decision-making in an IoT context requires new tools and models to exploit the new environment, such as big data generated from sensors and connected things (Ben-Daya et al. 2019).

(25) *Resilience strategies—BDA and AI* Analysis of how BDA and AI techniques can help with SC disruptions and the mechanics for achieving it. For example in global SCs where sales volumes and product variability are high and disperse, the analysis of SC big data (sales, buying behavior, product inventory, transportation channels, distribution frequency and production rates) can reduce demand uncertainty and sensor data in distribution centers which can mitigate logistics risks and increase visibility and trust among suppliers (Baryannis et al. 2019a, b). Some evidence also exists (Griffith et al. 2019) that the BDA and AI technologies can assist visibility (e.g. with open-source imagery tools and analytic mapping tools) in disaster relief chains and humanitarian logistics but how this can be done is a question that requires further investigation (Dubey et al. 2019abc).

(26) *Identification of suppliers based on proximity—machine learning algorithm* Development of a learning algorithm to deduce location-based relationships of suppliers by identifying the localization of suppliers from public data sources (Brintrup et al. 2019).

(27) *Large supply chain networks—BDA* Analysis of large-scale complex supply networks and their risks (as in their majority researchers illustrate their contributions using small cases) with the use of current digital technologies which facilitate collection of big data from across the SC. Having such test datasets of realistic size and complexity for SCs would result in more empirical insights (Bier et al. 2019).

4.14 Digital technologies

(28) *Blockchain—Survey, case study* Testing the hypothesis that implementing blockchain technology in SCs decreases opportunistic behavior of SC players like subtle violation of agreements and concealing of critical information due to the transparency, security, and auditability that the technology promotes (Saberi et al. 2019).

(29) *Blockchain—Survey, case study* Supply chain governance structure characteristics need to be evaluated for effectiveness in understanding blockchain-based SCs where no central authority is responsible for information management and validation. Analysis is required regarding who and what governs transactions, rules, and policies. Will operational relationships improve their outcome due to the features of blockchain technology, which do not require strategic formal coordination (Saberi et al. 2019)?

(30) *IoT—Survey, case study* Provision of guidance for IoT adoption from companies as to which process and where in the SC they should deploy IoT, given that SC partners may be at different stages of the IoT implementation (Ben-Daya et al. 2019).

4.15 Disease outbreaks/pandemics/COVID19

(31) *Pandemic—Mixed Methods* Measuring how the Covid-19 or other pandemics affect firms, employees, consumers, and markets for formulating effective policy responses to the challenges posed by the crisis (Hassan et al. 2020).

(32) *Pandemic—Modelling* Development of a contingency plan framework with operating policies for specific SCs deriving from the analysis of modeling techniques that simulate disease breakouts, as unlike other disruption risks, epidemic outbreaks start small but spread fast and disperse over many geographic regions creating increased uncertainty (Ivanov 2020a). A special case are products with high demand during disease outbreaks such as medical face masks, sanitizers, etc. Evaluation of the SC behaviors of adaptation, digitalization, preparedness, recovery, ripple effect, and sustainability during and after pandemics (Queiroz et al. 2020).

(33) *Pandemic—Modelling, case study* How do changing regulations due to the pandemic (lockdowns, changing working patterns, etc.) impact productivity throughout the supply chain? How do dark (fully automated) warehouses and other operational solutions for contactless or zero interaction among employees or employees with customers impact firms' performance, employees' work environments and customer experience? (Mollenkopf et al. 2020)

(34) *Pandemic/digital technologies—Modelling, case study* Investigation of the utilization of digital technologies, such as digital SC twins, omnichannel, additive and digital manufacturing, to support decision-making in long-term disruptions caused by pandemic outbreaks (Ivanov and Dolgui 2020).

5 Discussion

In this study, we aimed to present an overview of the literature in order to provide a picture of SC disturbances and resilience methods. We first mapped all relevant studies and provided a profile of the popular articles. The second part of the paper, through content analysis, presented the knowledge offered in selected articles in a comprehensive and narrative way. Both methods concluded in a synthesis of knowledge about SC disruptions and resilience methods which we believe are useful to researchers and managers alike.

5.1 Research implications

Our study has numerous implications for researchers. First, it provides a useful introduction to the field through the profiling study which focuses on the key literature. It shows that publications about SC disruptions started appearing after 2004 but the field has matured fast and in these 15-20 years is populated by many studies which explain and evaluate the impact of the adoption of certain response strategies to SC disruptions and risks. However, this is not to say that the field has been over-researched but on the contrary it has become as hot as ever due to the recent pandemic of COVID19 and the enormous disruptions that has caused to the whole world. Therefore, more research is required for specific and new types of disruptions but also in general for all types as innovative ways of building resilience are created by utilizing modelling techniques and new digital technologies. Two popular review studies on SC disruptions and risks are (Kleindorfer and Saad 2005; Tang 2006) and two more trending papers deal with Industry 4.0 (Ivanov et al. 2019) and blockchain (Saberi et al. 2019).

As SC disruptions occur in greater frequency and intensity (Zsidisin et al. 2016), we hierarchized them based on the literature by type, impact and occurrence, starting from the catastrophic events of low frequency and high impact and concluding with the infrastructural events of high occurrence but lower impact. Although the urge so far has been to research high occurrence but lower impact SC disruptions which cumulative cause a non-negligible and continuous problem to SCs (Zsidisin et al. 2016), the new unforeseen pandemic seems to rush research towards the other direction as already in 2020 a number of papers have been published in the particular topic, e.g.(Ivanov 2020a; Queiroz et al. 2020). Our study also examined the growing research on the ripple/snowball effect of perturbations originating in a localized point which amplifies consequences for the downstream SC echelons, as opposed to the bullwhip effect which impacts the SC upstream. The realizations of the ripple effect consequences is another reason for more research in SC disruptions with models that take into considerations many echelons across the SC.

Moreover, the study presents an analysis supported with examples of quantitative approaches which were used to model the SCs based on risk factors, their impacts, mitigation tactics' costs and benefits and what-if scenarios for testing certain strategies (Das and Lashkari 2015). Optimization is the mathematical method most often used for this purpose (stochastic programing, mixed-integer programing, multi-objective programing) followed by simulation techniques (system dynamics, discrete-event simulation, agent-based model and Monte-Carlo simulations) that can handle more uncertainty and complexity. Statistical analysis, graph theory and game theory are also among the modeling methods that are distinguished in the papers of our review. Many models incorporate a function of cost to measure the impact of disruptions and provide a cost–benefit analysis of mitigation or resilience actions.

There is also an attempt to benefit, with regards to data promptness and accuracy, from the operability with new digital solutions (e.g. IOT, BDA, machine learning) to build real-time reconfigurable SC models based on the incurring disruption and knowledge that has been accumulated from past reactions. These trends call for new principles and models to support SCM and populate the future research agenda. Such promising methods for dynamic supply-chain models are Agent-based models, which are configurable distributed software components that continually realign goals and processes (Blackhurst et al. 2005). In the research agenda of SC disruptions and the ripple effect, notable is the call for the development of quantitative decision-making models coupled with the new digital technologies' capabilities including blockchain contracts. Another area is the behavioral analysis of managers who interpret the automated generated knowledge and the importance of receiving training for tackling SC disruptions and increasing the level of preparedness. The study offers a long list of topics in the field that require immediate investigation from interested researchers. While the research dealing with disease outbreaks from the humanitarian logistics aspect provides a substantial body of knowledge, e.g. (Banomyong et al. 2019; Dubey et al. 2019abc), the literature on analyzing the impact of pandemics from a business point of view is still limited (Ivanov 2020a) but growing fast. Therefore a special focus is required with regards to SC disruptions caused due to pandemics, such as COVID19. New and fast changing regulations for lockdowns, transport guidelines and employees' working conditions call for urgent understanding and evaluation of their effect in the SCs and identification of appropriate ways to react and adapt with the minimum possible distraction.

5.2 Managerial implications

The review part of this study has also identified several interesting points with managerial applicability.

The literature brings up several recovery and resilient strategies and methods that firms choose to adopt either in isolation or in coordination with the other SC echelons. The aim should be to build resilience to reduce or avoid disruptions (Hosseini et al. 2019a). Popular resilience strategies are redundancy building through safety stock, capacity reservations and multiple sourcing but more effective is considered the flexibility acquisition strategy through alternative suppliers, contingency plans and the adoption of ICT for information access, tracing, monitoring, warning, reporting and prediction of SC risk for fast response and rescheduling of operations (Centobelli et al. 2019). Moreover, information-sharing, collaborative communication with the other SC echelons, joint relationship efforts from the product/service design until its delivery and the reverse logistics flow and decision synchronization utilizing ICT capabilities (Nakano and Lau 2020) are all cost-effective ways for building resilience to SC disruptions and minimizing the occurrences and the duration of man-made disruptions.

Digital technologies have also played a crucial role, maybe the most important of all, in the improvement of SC performance enabling new capabilities of real-time reconfigurations and fast response and implementation of emergency plans in cases of disruptions. While the individual contributors (e.g. robots, sensors, RFID, agents, modular factories, etc.) are not new, they are becoming more approachable and companies more receptive to using them to stay competitive. More recent technologies, such as the IOT, augmented reality, Industry 4.0, 3D printing, BDA, artificial intelligence and blockchain are all examples of tools that are progressively changing the way SCs are organized. The level of accuracy, transparency, traceability and flexibility is immensely growing, transforming SCs to systems which continuously evolve and can be reconfigured on demand. Involvement of such technologies, which are often characterized as disruptive to the traditional SC model, have the potential to shrink SCs, and also produce better quality, reduce product development times, increase customized offerings to customers (Viswanadham 2018) and be more prepared for timely reactions to perturbations. Applicability studies of these technologies in the business environment are part of the future agenda. More importantly at the current situation of the rapid-spreading pandemic which has caused so many SC disruptions the whole business world is changing the business model by fast-tracking digital transformation to increase chances of survival.

Natural disasters and disease outbreaks consequences can be mitigated through resilient management of the relief SC operation. Development of trust between humanitarian organisations and other partners/stakeholders is necessary for coping with complex tasks during disaster relief and following standard code of ethics (Awasthy et al. 2019). Therefore, a focus on metrics and performance measurement such as delivery time, number of saved lives, the quantity of distributed relief items, and operations' costs is essential in order to empower the effectiveness and long-term relationships of the humanitarian aids and relief SCs (Baharmand et al. 2019). Foremost, research emphasizes the development of flexible resiliency strategies with assisting technological solutions, such as BDA and AI technologies offering open-source imagery tools and analytic mapping tools in humanitarian logistics, for improving responsiveness through information and materials pipeline visibility and increased effectiveness of processes through better management of the scene (Griffith et al. 2019). Flexible networks with prompt rescheduling functions can achieve the required balance between speed and quality of the survival processes.

6 Conclusions

IT professionals continually develop new applications with big data capabilities to help stakeholders increase value (Galetsi et al. 2019), thus there are expectations for the allocation of higher budgets towards IT infrastructure and BDA experts (Galetsi et al. 2020). Investing in appropriate technology and quality information sharing helps with SC visibility, enhances trust and cooperation among SC partners and eventually leads to a more resilient SC (Dubey et al. 2019a,b,c; Kamalahmadi and Mellat-Parast 2016) against disruptive events. This should be the focus of the top administration of each firm alone and in collaboration with the other echelons of their SC. Supply chains should embrace the TQM (total quality management) philosophy of prevention, as studies have shown that building resilience is less costly than recovering from problems (Jabbarzadeh et al. 2018). Yet, it is impossible to completely avoid disruption and attention should also be drawn to the recovery policies regardless of what caused the disruption. Therefore, human-driven adaptation first, followed by computer-driven adaptation, is needed to change SC plans, inventory policies and schedules to achieve the desired performance, which is the precondition of stability and robustness (Ivanov et al. 2013). As SCs become more global and complex, the impact of any disruption intensifies. The answer is building resilience by incorporating longer term partnerships, government policy that enables flexibility, an IT approach that fosters business continuity (Wright 2013) and a culture of readiness in contingency actions.

Appendix

See Tables 3, 4, 5, 6.

Table 3 Top 10 referenced articles in supply chain disruptions

	TITLE – JOURNAL - Ref	Contribution
1	Perspectives in Supply Chain Risk Management. *International Journal of Production Economics* Tang (2006)	It develops a framework for classifying SC risk management literature. It reviews quantitative models for managing SC risks and relates such strategies with actual practices. One of the first reviews to provide a holistic approach for tackling risks with effective supply contracts information sharing, demand shifting, product postponement, etc.
2	Managing Disruption Risks in Supply Chains. *Production & Operations Management* Kleindorfer and Saad (2005)	It provides a conceptual framework for SC disruptions' management, depicting actions of risk assessment and mitigation followed by empirical results from accidents in the chemical industry. It is one of the early studies to discuss the concepts of SC disruptions
3	Managing Risk to Avoid Supply-chain Breakdown. *MIT Sloan Management Review* Chopra and Sodhi (2004)	An overview of risk factors for SC disruptions and mitigation strategies supported by real case examples. Textbook style
4	On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science* Tomlin (2006)	It explores sourcing strategies by developing an inventory-optimization problem for risk-averse and risk-neutral firms' decisions between the selection of an unreliable supplier and a reliable one that is more expensive
5	The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences* Craighead et al. (2007)	Through semi-structured interviews and focus groups the paper explores how and why one SC disruption could be more severe than another. It presents six propositions that relate to the severity of SC disruptions to three SC design characteristics of density, complexity, and node and to two SC mitigation capabilities of recovery and warning
6	An empirical analysis of the effect of supply chain disruptions on long-run stock price performance and equity risk of the firm Hendricks and Singhal (2005)	The study investigates the impact of 827 disruption announcements made the period 1989–2000 to the stock price of SC disruptions. It shows that the average stock returns of disrupted firms are nearly −40% and the effect lasts for 1 year after disruption. This is one of the series of studies published by the authors on the idea of financial effect of operations management
7	The organizational antecedents of a firm's supply chain agility for risk mitigation and response." *Journal of Operations Management* Braunscheidel and Suresh (2009)	A survey on SC professionals followed by a statistical modelling identified that internal integration, external integration with key suppliers and customers, and external flexibility to have significant positive impact on the firm's supply chain agility
8	Understanding the concept of supply chain resilience *International Journal of Logistics Management* Ponomarov and Holcomb(2009)	A review which sets the basis for explaining SC resilience and for the development of a conceptual model. It identifies that resilience had yet to be researched from the logistics perspective
9	Global supply chain risk management strategies." International *Journal of Physical Distribution & Logistics Management*. Manuj and Mentzer (2008)	A survey (interview-based with senior SC executives) and review study exploring risk management strategies in global supply chains, and building a theoretical model based on demand, supply and operational risks
10	Identifying risk issues and research advancements in supply chain risk management." *International Journal of Production Economics Tang and Musa* (2011)	A review and profiling study that investigates the research development in SC risk management using citation/co-citation analysis

Table 4 Top 10 trending* papers on supply chain disruptions

	TITLE–JOURNAL-Ref	Contribution
1	The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research.* Ivanov et al. (2019)	It analyses future transformations towards cyber-physical SCs and the impact of digitalisation (big data analytics, Industry 4.0, additive manufacturing, advanced trace & tracking systems) of SCs on the ripple effect control and SC disruptions
2	Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research* Saberi et al. (2019)	It discusses blockchain technology and smart contracts and their potential application to SCM to mitigate risks
3	Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review* (Hosseini et al. 2019a)	It presents a systematic review and profiling study of recent literature on SC risks and analyses the quantitative methods can be used at different levels of capacity resilience
4	Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA. *International Journal of Information Management*. Queiroz and Wamba (2019)	A survey and statistical modeling of the employee' attitudes towards the adoption of blockchain technology. Factors that positively affect the behavioral intention to adopt blockchain are facilitating conditions and trust between SC stakeholders
5	Low-Certainty-Need (LCN) supply chains: a new perspective in managing disruption risks and resilience. *International Journal of Production Research* Ivanov and Dolgui (2019)	It presents a new conceptual approach to SC design with a low need for certainty, less dependent on the unpredictability of disruptive changes
6	Ripple effect in the supply chain: an analysis and recent literature. *International Journal of Production Research* Dolgui et al. (2018)	A follow-up review study which thoroughly presents the ripple effect in SCs by describing its reasons, the quantitative models for its analysis and research gaps
7	OR/MS models for supply chain disruptions: a review. IIE Transactions Snyder et al. (2016)	A review of 180 OR modelling studies on SC disruptions organized under evaluation of SC disruptions, strategic and sourcing decisions, contracts and incentives, inventory; and facility location
8	A critical review on supply chain risk–Definition, measure and modeling. *Omega* Heckmann et al. (2015)	A review of quantitative SC risk management approaches also emphasizing the definition of SC risk and related concepts
9	Supply chain risk management: a literature review. *International Journal of Production Research* Ho et al. (2015)	Classification of studies based on risk factors, types, industries and the use of quantitative modeling methods and qualitative techniques
10	Researchers' Perspectives on Supply Chain Risk Management. *Production and operations management* Sodhi et al. (2012)	A survey using open-ended questions to focus groups of professionals (members of Supply Chain Thought Leaders, International SCRM groups, Operations and SC management researchers of INFORMS). The survey identified gaps related to the definition of SCRM, the experiences of risk incidents, and the use of empirical methods

*(6 hot papers as characterized by WoS because were published in the past 2 years and received enough citations to be in the top 0.1% of papers in their academic field and 4 papers with a high average citation per year index)

Table 5 Ten indicative examples of papers applying quantitative techniques

Modeling technique	Disruption response	Ref.	Example description
Optimization: mixed-integer nonlinear programming	Multiple sourcing	Amini and Li (2011)	The hybrid optimization model represents a supply chain configuration for a new product diffusion that allows the manufacturer to source from multiple suppliers and modes and determines safety stock placement decisions based on demand dynamics throughout the product's life cycle. The multiple-sourcing approach is superior to single-sourcing on the overall supply chain performance in an environment with random supply disruptions.
Optimization: stochastic programming model	Risk – Costs performance	Snoeck et al. (2019)	A two-stage stochastic programing model is developed to assess the costs of disruptions and the SC mitigation options incorporating a conditional value at risk in the model's objective function to depict the risk averted decision-makers. Using the case of a chemical SC, the results show the trade-off between long-term costs minimization and short term risk minimization, which latter leads to a more aggressive investment policy.
Simulation: System dynamics	Information Sharing	Kochan et al. (2018)	The study builds two system dynamics models one representing traditional and the other cloud-based information sharing in a hospital supply chain and simulates their performance The findings show that cloud-based information sharing improves visibility and hospital's responsiveness to accommodate fluctuations in patient demand and supply lead times.
Simulation: hybrid model (discrete-event simulation and agent-based model)	Ripple effect—Capacity change	Ivanov (2017)	The study models the ripple effect using a discrete-event simulation model of which each structural model object is an agent. Demand forecasts are set up based on historical data and periodic demand. Ordering incorporates sourcing policies from distribution centers (DCs) to customers (e.g. single or multiple sourcing) and inventory control policies at DCs. Production includes sourcing policies from factories to DCs and inventory policies at factories. Under transportation, vehicle types and path data are set-up. By decreasing capacities (capacity disruptions) at different points in time and for different durations, performance impacts are observed for different scenarios. Performance measures include revenue, costs, lead time, delayed orders and service level.
Simulation: discrete-event simulation	Ripple effect–single-multiple sourcing/capacity change	Ivanov (2018)	The detailed large-scale discrete-event simulation model replicates the supply chain of a smartphone and under the execution of different scenarios it determines the factors that mitigate the ripple effect (facility fortification at major employers in regions) and the factors that enhance the effect (single sourcing, reduction of storage facilities downstream the SC).

Table 5 (continued)

Modeling technique	Disruption response	Ref.	Example description
Simulation: agent-based model	Supplier selection	Hou et al. (2018)	An agent-based simulation model is built of a SC network where each firm is modeled as an agent who selects suppliers based on trust, selling price or just randomly. The model shows that the trust-based rule is the most robust against disruptions.
Control theory and time-continuous simulation	Information sharing—Bullwhip effect	Yang and Fan (2016)	By using control theory modeling and simulation this study analyses three two-echelon SCs with different information management strategies [traditional, information sharing and collaborative planning, forecasting and replenishment (CPFR)] and assesses how these contribute to mitigating operational and disruption demand risks. System stability, recovery time and demand shock amplification are taken as performance metrics when the SC is under a demand disruption. Results show that SCs with popular information management strategies are not evidently more stable than traditional ones.
Game theory	Supplier reliability	Fang and Shou (2015)	This paper uses game theory to examine the Cournot competition between two SCs. Each SC comprises a retailer and an exclusive supplier with random yield. The model evaluates the impact of supply uncertainty and competition intensity on the equilibrium decisions of ordering quantity, contract offering and centralization choice. One finding is that a retailer should order more if its competing retailer's supply becomes less reliable or if its own supplier becomes more reliable.
Graph theory	Supply risk	Nakatani et al. (2018)	Graph theory is used to model a SC with domestic and imported raw materials with chance of disruption and evaluates the SC vulnerability as determined by market concentration. Using a case study of the Japanese synthetic resins SC the model identifies the bottleneck raw materials.
Statistical analysis: Structural equation modeling (SEM)	Building resilience	Brusset and Teller (2017)	The results of a survey of 171 SC managers with the use of structural equation modeling evaluate the relationships among SC capabilities, resilience and SC risks presented in a conceptual model. The findings show that resilience is imrpoved when the SC exhibits high flexibility and strong integration between its echelons.

Table 6 Contribution of literature on the ripple effect

Methods	Contribution-References
Literature review	Review and overview analysis to introduce the ripple effect in SCs; reasons for happening, modelling approaches for describing the phenomenon and its impact, mitigation strategies and future research Dolgui et al. (2018), Ivanov et al. (2014a, b)
Bibliometric analysis	Bibliometric analysis with network and meta-analysis techniques to classify research in clusters and identify current and future research on the field (Mishra et al. 2019).
Viewpoint	A conceptual framework for researching the relationships between digitalization (big data analytics, Industry 4.0, additive manufacturing, trace & tracking systems) and SC disruptions and how IT applications can control the ripple effect (Ivanov et al. 2019)
Interviews-case study-observations	Environmental directives for greening a SC and the ripple effect these enforcements may have on the SC, acknowledging the importance of SC partners collaboration at the planning stage (Koh et al. 2012)
Survey	Executives' survey about their perceptions on the impact and causes of SC risks, actions they take to address them and challenges they face (Marchese and Paramasivam 2013)
Simulation models	A simulation study of a real distribution case in the beverage sector to investigate the interrelations of the bullwhip and ripple effect. The findings show that the ripple effect can be a bullwhip-effect driver, while the latter can be launched by a severe disruption even in the downstream direction (Dolgui et al. 2019) Development of multi-stage SC hybrid models consider capacity/sourcing disruptions in order to measure the ripple effect impact and identify recovery strategies. The studies contribute to the identification of major areas of simulation application to the ripple effect modelling (Hosseini et al. 2019b; Ivanov 2017). A model for reactive recovery policies in the dairy SC under conditions of the ripple effect (Ivanov et al. 2016a, b)
Mathematical models	Modelling of protection plans of large area disruptions where the ripple effect distresses entire regions by analyzing the 2009 L'Aquila earthquake case. The single-level mixed-integer model applied to a tree-search procedure identifies which facilities to protect (Liberatore et al. 2012). Development of linear programming models of multi-period, multi-commodity production–distribution/transportation SC models with disruptions and the ripple effect consideration in order to aid decision making in reconfiguring the network design (Ivanov et al. 2015, 2013) With a focus on the modelling aspect of a multi-stage, multi-period, and multi-commodity problem settings are developed for multi-objective decision-making on optimal distribution planning for an upstream centralized network taking into account structure dynamics and the ripple effect of different disturbances (Ivanov et al. 2014a, b) The contribution of this study is to establish an interrelation between the disruption scenarios of different risk aversions and the optimization of the SC reconfiguration paths for recovery (Pavlov et al. 2019) A Bayesian network approach for SC resilience measure with a multi-stage assessment of suppliers' proneness to disruptions (included for the first time in the literature) considering also SC propagation. (Hosseini and Ivanov 2019)

Table 6 (continued)

Methods	Contribution-References
Optimization and simulation	A multi-echelon inventory model to assess the ripple effect of a supplier disruption, with the addition that the study combines features of financial, customer, and operational performance based on possible maximum loss (Kinra et al. 2019).
Multi-criteria model	A multi-criteria approach based on the analytic hierarchy process method to select a SC design under the ripple effect consideration by integrating operability objectives as new KPIs (resilience, stability, robustness) into SC decisions (Sokolov et al. 2016)
Graph model	A multi-level graph model of the SC with an entropic approach which is capable of defining SC risks for the identification and quantification of the ripple effect (Levner and Ptuskin 2018)

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