

Quantitative models for risk management in the supply chain: a review with a focus on pandemics

Abstract

Supply chain risk management is considered a topic of increasing interest worldwide and its focus has evolved over time. The recent coronavirus pandemic (known as COVID-19) has forced business to handle a new global crisis and rapidly adapt to unexpected challenges. In an attempt to help companies counteract the pandemic risk, as well as to fuel the scientific discussion about this topic, this paper proposes a systematic literature review on risk management and disruptions in the supply chain focusing on quantitative models and paying a particular attention on pandemic emergencies. With this aim in mind, the relevant aspects of pandemics risk management have been first identified and models published in the past literature have been analysed with the aim of evaluate their suitability of being applied to sanitary crises. At the same time, in carrying out the analysis of the literature, the study moves from previous reviews about risk management and updates them, starting from the lines of research that have been covered in recent years and evaluating their consistency with future research directions emerging also as a consequence of the pandemic crisis. Gaps and limitations of the existing models are identified and future research directions for pandemics risk management are suggested.

Keywords: systematic literature review; risk management; pandemics; models; supply chain.

1 Introduction

In complex systems such as supply chains, where integrated flows of materials and information take place beyond the boundaries of individual companies, a substantial degree of inherent uncertainty cannot be avoided (see, e.g., Prater, 2005). Besides, that uncertainty may increase significantly when unexpected disruptions occur. Evidence of this is given by the current crisis due to the coronavirus pandemic (known as COVID-19) which is expected to create an economic depression even more severe than the 2008 financial crisis (Jenny, 2020). This is already true today for certain economic sectors such as travel and tourism, food and agriculture, retail, healthcare systems and academic institutions (Shrestha et al., 2020).

More formally, when discussing risk, it is fundamental to distinguish between the so-called ripple effect and bullwhip effect (Dolgui et al., 2018). While the latter deals with the operational and recurrent risks in a supply chain (e.g., demand fluctuation), the ripple effect deals with low-frequency/high-impact disruptions or exceptional risks, such as the risk of a pandemic outbreak. Dolgui et al. (2018) have also highlighted that the ripple effect impacts on the structural dynamics of the supply chain which, consequently, may require middle- and long-term recovery with high coordination efforts and investments.

It is therefore self-evident that modelling approaches for dealing with the risk of disruptions in supply chains are considered a topic of increasing relevance worldwide. In this respect, it is of certain interest to analyse how previous literature reviews about supply chain risk management (SCRM) and disruptions have evolved their arguments in the last years by changing their focus from the definition and measurement of risk to the identification of the possible strategies which may allow supply chains

to adapt themselves, restore acceptable levels of performance, handle uncertainty and, consequently, deal with the aforementioned ripple effect.

Going back over 10 years ago, Khan and Burnes (2007) have analysed the definition of risk by debating about its origin and evolution over time. Then, the authors describe the relationship between risk and uncertainty by adopting the following viewpoint: whilst uncertainty may not be measurable, it is nonetheless a key driver of risk which, instead, is both measurable and manageable. Lastly, the authors have emphasised the need for SCRM models, capable to incorporate risk management tools and techniques from other areas of research (e.g., from the financial area).

This difference between risk and uncertainty has been discussed also by Tang and Nurmaya Musa (2011). In this case, the authors propose a definition of risk based on two key elements: (i) it is related to events with small probability but that may occur abruptly; and (ii) it is associated with negative consequences. They also classify the main supply chain risks as follows: (i) the *material flow* risk, which originates into the stages of source, make and deliver; (ii) the *financial flow* risk, which involves improper investments and the inability to settle payments; (iii) the *information flow* risk, which is related to issues such as information accuracy and security. Once again, the suggested research guidelines include an integration of knowledge from multiple research domains.

Subsequently, the literature review by Durach et al. (2015) has narrowed down the perspective by focussing on the concept of supply chain robustness, which the authors define as the ability of a supply chain to resist or avoid change. In the same year, other reviews (by Fahimnia et al., 2015, and Heckmann et al., 2015) have broadened the debate about the taxonomies and perspectives within the context of SCRM, thus stressing the lack of clear definitions in the literature. Specifically, the interesting work by Heckmann et al. (2015) has provided a comprehensive definition of supply chain risk as follows: “supply chain risk is the potential loss for a supply chain in terms of its target values of efficiency and effectiveness evoked by uncertain developments of supply chain characteristics whose changes were caused by the occurrence of triggering-events”. Those triggering-events can be referred to as different synonyms such as disturbances, disasters, hazards, crises and, often used in the literature, disruptions. In general, the more susceptible to risk, the more vulnerable a supply chain is. The same authors have also provided a clear definition of supply chain resilience, that is the “supply chain’s ability to return to its original or move to a new, more desirable state after being disturbed”. In other words, according to the authors, a resilient supply chain may also improve its performance (reaching a “more desirable state”) after the occurrence of undesired triggering-events.

A more acute focus on recovery considerations can be found in Ivanov et al. (2017). The authors have discussed two approaches that can be adopted to protect supply chains against disruptions, namely the *proactive* approach, which aims at creating certain protections without recovery considerations, and the *reactive* approach, which aims at adjusting the processes and structures of a supply chain after disruptions have occurred. In their proposed research agenda, the authors highlight the need for integrating operability objectives and new performance indicators (e.g., supply chain resilience) and investigating the dynamic behaviour of the supply chain. A focus on the dynamic risk behaviour of a supply chain can also be found in the review by Bugert and Lasch (2018), where the following formal definition of a supply chain disruption model is presented: such a model “represents a supply chain and all relevant potential triggering events which can potentially impede the supply chain from achieving its operational goals and/or jeopardize the existence of one or more supply chain entities and includes all necessary static and dynamic features to describe potential losses for all supply chain partners in terms of the supply chain’s target values in order to support the coordinated approach amongst supply chain entities to reduce supply chain vulnerability and to increase the supply chain’s predicted ability to return to a stable state after experiencing disruptions in the real system”.

More recently, Hosseini et al. (2019) have proposed an interesting review of quantitative methods for supply chain resilience analysis which focuses on three lines of defence. The first line of defence is called *absorptive* capacity and acts prior to a disruption occurring. The second line of defence is the *adaptive* capacity and refers to the capability of the supply chain to overcome disruptions by implementing nonstandard operating practices without any recovery activities. The third line of defence is the *restorative* capacity, reflecting the ability of a system to be restored quickly and efficiently when the other lines of defence fail. Based on these lines of defence, the authors propose a new definition of supply chain resilience as follows: the “capability to utilize the absorptive capacity of supply chain entities to repulse and withstand the impacts of perturbations, to minimize the consequences of disruptions and their propagation by utilizing adaptive capacity and to recover performance level to normal operations in a cost-efficient manner using restorative capacity when absorptive and adaptive capacities are not sufficient.” Finally, the authors recommend future research directions on both the methodology side, with particular reference to multi-objective stochastic models, and the subject side, with particular reference to the need of including environmental and social objectives in the SCRM, as well as the opportunity of achieving resilience through Industry 4.0 and digital technology tools. The relationship between Big Data, Industry 4.0 and SCRM, along with the need for a more holistic vision has also been highlighted by Fagundes et al. (2020), who have presented one of the most recent review on decision-making models and support systems for supply chain risk.

For the sake of this overview, it can also be noted that recent reviews have been conducted about some specific aspects of risk management in supply chains. Those reviews can be categorised as follows: (i) reviews on specific decision problems/risk categories; (ii) reviews on specific industrial sectors; (iii) reviews on specific modelling approaches and techniques. As regards the first group of reviews, Hamdi et al. (2018) have dealt with the supplier selection problem under SCRM. Rebs et al. (2018) have evaluated the stakeholder’s influence on sustainable supply chain management by taking into account economic, environmental and social risks. Colicchia et al. (2019) consider the exposure of supply chains to the so-called “information risks”, such as intentional or non-intentional leakage of information and attacks by hackers. Examples of studies belonging to the second category of reviews are those by Behzadi et al. (2018), who have dealt with agricultural supply chains, and by Al-Haidous and Al-Ansari (2020), who have focused on liquefied natural gas supply chains. As regard the last category, the number of reviews on specific modelling approaches and techniques is quite limited. Some examples are the works of Snyder et al. (2016), who have reviewed the Operations Research/Management Science (OR/MS) literature on supply chain disruptions, and Rebs et al. (2019) who have discussed the recent developments in System Dynamics modelling for supply chain management.

The literature reviews discussed above are summarized in Table 1, where some relevant pieces of information are also shown, namely: the article citation; the indication whether the article focuses on a specific industrial sector or not; the type of reviewed models (quantitative, qualitative or both); the search database used by the authors; the review timespan; the number of works reviewed; the review methodology (LR = Literature Review; SLR = Systematic Literature Review; BNA = Bibliometric/citation Network Analysis); and the suggested researched directions. This latter has been divided into four main issues that have emerged as relevant from this analysis: (i) the evaluation of Industry 4.0/digital tools, (ii) the inclusion of environmental/social risks, (iii) the need for multi-criteria (and multi-disciplinary) approaches, (iv) the need for empirical applications and model validation techniques.

Moving from previously published reviews, this paper proposes an updated analysis of the literature on risk management and disruptions in the supply chain, with a particular focus on quantitative models and on the management of a particular risk, such as pandemic emergencies. The chosen research

methodology is therefore the systematic literature review. The aim of this paper is twofold. First, this study looks at the lines of the research on risk management that have been covered in recent years and evaluates their consistency with the future research directions suggested in literature. Second, this paper has a key distinguished feature compared to previously published reviews, in that it evaluates risk management studies trying to focus on their suitability for being applied to the very timely issue of pandemic emergencies. Pandemic crises are a very recent topic, and as such, it is hard to believe that quantitative models are already available for counteracting this emergency. Hence, this review makes an attempt to identify the models published in the past literature that, although not focusing exactly on pandemic emergencies, can nonetheless be applied to these situations. To achieve this aim, a comprehensive set of detailed pieces of information are recorded for each study reviewed and a detailed classification scheme is proposed. In reviewing the literature, some specific classification fields will be used to expressly evaluate the usability of the available models for managing pandemic emergencies.

The remainder of the paper is organised as follows. After this introduction, section 2 details the methodological approach followed to create the sample of papers included in the review, together with the classification scheme proposed for the analysis of these papers. Section 3 details the results of the review, which consist in some descriptive statistics followed by a detailed analysis of the studies reviewed, including their possible usability for pandemic emergencies. Section 4 discusses the implications and limitations of this study and outlines future research directions.

Article citation	Reviewed models	Search database	Author Keywords	Methodology	Specific industrial sector	Timespan of the review	Number of studies reviewed	Suggested future research directions			
								Industry 4.0 / digital tools	Environmental / social risks	Multi-criteria approaches	Empirical applications
Fagundes et al. (2020)	Quantitative	Scopus	Bibliometrics; Multicriteria decision; Risk model; Stochastic and computational model	SLR; BNA		2001-2018	350	X	X	X	X
Al-Haidous & Al-Ansari (2020)	Quantitative	Multiple scientific databases	Closed loop; Forward loop; LNG; Optimisation; Resilience	SLR	Oil and gas	2000-2019	44		X	X	
Hosseini et al. (2019)	Quantitative	Google Scholar and Scopus	Capacity resilience; Digital supply chain; Disruption risk; Resilience supplier; Resilient supply chain; Review; Ripple effect; Supply chain resilience; Supply disruptions	SLR; BNA		2002-2017	168	X	X	X	
Rebs et al. (2019)	Quantitative	Web of Science	Conceptual framework; Literature review; Risk management; Stakeholder influences; Sustainable supply chain management; System dynamics	SLR; BNA		1998-2017	102			X	X
Colicchia et al. (2019)	Quantitative/Qualitative	Scopus	Resilience; Risk management; Supply chain disruptions; Supply chain vulnerability; Supply-chain management; Systematic literature review	SLR; BNA		1998-2017	309			X	X
Behzadi et al. (2018)	Quantitative	Scopus	Agribusiness supply chain; Resilient; Risk management; Robust	SLR	Agriculture	1993-2017	42			X	X
Rebs et al. (2018)	Quantitative/Qualitative	Web of Science	Conceptual frameworks; Empirical studies; Formal models; Literature review; Risk management; Stakeholder influences; Sustainable supply chain management	SLR; BNA		1994-2014	90		X	X	
Hamdi et al. (2018)	Quantitative/Qualitative	Multiple scientific databases	Hybrid approach; Optimization of a supply portfolio; Qualitative approaches; Quantitative approaches; Simulation approach; SCRM	SLR		2003-2014	124			X	
Dolgui et al. (2018)	Quantitative	Not specified	supply chain design; supply chain dynamics; supply chain engineering; supply chain resilience; SCRMt	LR		2005-2017	Not specified	X	X	X	X
Bugert & Lasch (2018)	Quantitative	Multiple scientific databases	Modeling; Risk analysis; Risk management; Simulation; Supply chain disruption; SCRM	SLR		2001-2018	57			X	X
Ivanov et al. (2017)	Quantitative	Not specified	supply chain design; supply chain dynamics; supply chain engineering; supply chain resilience; SCRM	LR		2001-2017	Not specified			X	
Snyder et al. (2016)	Quantitative	Not specified	Not specified	LR		1979-2015	180			X	
Heckmann et al. (2015)	Quantitative/Qualitative	Not specified	Complexity; Resilience; Risk definition; Supply chain management; Uncertainty; Vulnerability	LR		1987-2014	Not specified			X	
Fahimnia et al. (2015)	Quantitative	Scopus	Bibliometrics and network analysis; Quantitative Model; Review; Supply Chain Risk; Uncertainty	SLR; BNA		1978-2013	1108		X	X	
Durach et al. (2015)	Quantitative/Qualitative	Multiple scientific databases	Antecedents; Dimensions; Supply chain robustness; Systematic literature review	SLR		2002-2013	94				X
Tang et al. (2011)	Quantitative/Qualitative	Web of Science	Citation/co-citation analysis; Risk management; Supply chain	SLR; BNA		1995-2009	138			X	
Khan & Burnes (2007)	Quantitative/Qualitative	Not specified	Risk analysis; Risk management; Supply chain management	LR		1921-2005	Not specified			X	X

LR = Literature Review; SLR = Systematic Literature Review; BNA = Bibliometric/citation Network Analysis

Table 1: summary of the previous reviews on risk management.

2 Methodology

2.1 Sample construction

A systematic literature review (Tranfield et al., 2003) is a two-step approach: the first step is the definition of the inclusion criteria, which should enable the correct selection of pertinent and relevant studies to be reviewed; the second step is the definition of the strategy for locating and selecting the studies (Alderson et al., 2004). Compared to a traditional review, this approach is more structured and, most importantly, replicable.

As far as the first step is concerned, in this paper we have only included studies:

1. written in English and published in peer-reviewed international journals;
2. expressly focused on proposing technical approaches to risk management in the supply chain.

Looking at the second step, studies were found by carrying out a computerized search using the Scopus database (<http://www.scopus.com/>), which is one of the largest available databases of scientific publications and is expected to cover almost the whole amount of papers relating to the subject under investigation.

To comply with inclusion criterion 2 above, an appropriate set of terms relating to supply chain, risk, risk management, disruptions and quantitative models was preliminarily identified. In particular, three groups of keywords were combined for making the search:

- Group 1 included the terms “supply chain” and “logistics”;
- Group 2 included the terms “risk management”, “disruption” and “pandemic”;
- Group 3 consist of the term “quantitative”, which, in line with a previous study (Bugert & Lasch, 2018), was used to expressively focus on technical approaches and models.

A single query was made in September 2020 in the Scopus database by combining the terms of the same group with the OR operator and the different groups with the AND operator. These terms were searched for in the article title, abstract or keywords of the paper, to ensure that the study focused on the chosen theme; the resulting structure of the query was: *TITLE-ABS-KEY ("supply chain" OR "logistics") AND TITLE-ABS-KEY ("risk management" OR "disruption" OR "pandemic") AND TITLE-ABS-KEY ("quantitative")*.

Moreover, in line with inclusion criterion 1, the query was limited to journal papers type “article” or “review” (excluding other forms of publications), whose language is “English”. As far as the timespan is concerned, only year 2021 was excluded; indeed, at the time of the query, only a small number of papers relating to 2021 was already available on Scopus.

The query returned a total of 192 papers, that were retrieved and screened by reading the full document, to ensure that they comply with the inclusion criteria. After reading, some papers were excluded from the original sample because of the following reasons:

- Despite the query settings, one paper was actually published on conference proceedings, probably because of a wrong classification on Scopus, and two papers were not written in English;
- 26 studies were review papers, i.e. papers that collect and classify previous studies on a specific topic. These studies were retrieved and examined, and the most relevant ones (17) were used for delineating the previous review papers available about risk management and supply chain. Results of their analysis has been already presented in section 1; hence, these studies are not analysed further;

- 64 papers were excluded because they were out of scope for the present review. Examples of these papers are studies whose central topic was different from risk management in the supply chain, or that do not expressively focus on disruptions or that targeted research fields very different from the supply chain context (e.g., the medical, biological or chemical areas). Similarly, purely conceptual papers, which although discussing the topic of risk, lack the presentation of any risk model, were excluded from the analysis as well.

The screening therefore led to excluding 93 papers overall, resulting in a final sample of 99 papers.

2.2 Papers classification

The 99 papers belonging to the final sample were all research papers, i.e. papers in which the authors describe the results of their own scientific activities. These papers were further classified into 2 macro-categories, depending on the specific type of research, as follows:

1. *quantitative papers* (48): these papers propose, develop or test quantitative models for risk management in the supply chain. According with definitions available in literature (e.g., Bondavalli et al., 2009), by quantitative model we mean a theoretical and formal description of a system or process translated into the language of mathematics;
2. *quali-quantitative papers* (51): papers that did not provide a fully quantitative approach were labelled as “quali-quantitative papers”. In these studies, the problem faced is described in a more abstract form, focusing on causality but not providing mathematical equations (Yan et al., 2013). Nonetheless, because of the usage of “quantitative” as a search keyword, these papers owns some quantitative aspects, meaning that the authors applied transdisciplinary or mixed research methods, including both quantitative approaches and qualitative ones (Bell, 2007).

2.2.1 Classification fields

For all the papers, an articulated set of data was collected by analysing the full documents. The full list of the key data collected is proposed in Table 2, together with a description of the relevant classification options. Some data, mainly of descriptive nature, are common across the two categories of papers; at the same time, however, because of the intrinsic difference between quali-quantitative and quantitative papers, additional data are specific to the two categories; the same holds true for the analyses made on the documents. The list of common data includes:

1. Paper’s *metadata*, i.e. title, authors, journal, year of publication, volume, number and pages;
2. *Country*, i.e. the nationality of the study. To determine it, we checked expressively the location in which the authors carried out the study or the application of their model as described in the full paper. This logic was preferred compared to more traditional approaches (e.g. determining the nationality of the study looking at the affiliation of the first author – see e.g. Gao et al. 2017), because of two reasons. First, it simultaneously allows for checking the existence of an application for the proposed model, which is relevant for establishing if the proposed model has been tested in a real case. Second, in some cases the studies have been found to span across more countries; this aspect could not be captured if looking at the nationality of a single author only;
3. *Main topic*, which reflects the paper macro-theme. Relating classification options were derived from the detailed read of the sample of papers;
4. *Industry context*, i.e. the industry field in which the research has been carried out;
5. Reference to *Industry 4.0*, *sustainability* or *emergency management*. As far as the former aspects are concerned, recent studies have shown that Industry 4.0 technologies have potential to enhance risk management (e.g., Ivanov & Dolgui, 2020). Similarly, sustainability, besides being a widely debated issue in literature, has been found to have relationships with

risk management in supply chains (e.g. Hallikas et al., 2020). The reference to emergency management was added with the primary aim to identify models that could be applied to crisis situations such as those involved by the COVID-19 pandemics, although not explicitly referring to the recent pandemic emergency. These classification fields were simply filled with Y/N, to keep track of possible relationships of the paper to the three areas mentioned. The considerations proposed in Table 2 formed the basis for the classification of the papers according to these areas;

6. *Disruption type – level 1*. This field details the macro-categorization of supply chain disruptions dealt with in the paper as proposed by Christopher and Peck (2004) or a combination of them;
7. *Disruption type – level 2*. For disruptions classified as *external to the company*, *internal to the supply chain network* or *external to the network*, a second-level classification is provided, in line with Christopher and Peck (2004) and World Economic Forum (2021) respectively;
8. *Approach type*. Models were labelled as *reactive* or *proactive* depending on their capability of eliminating disruptions before they have a chance to appear or of responding to events after they have happened (Ivanov et al., 2017);
9. *Model type*, which is used to detail the specific type of model developed in the study. Classification options different depending on the category of paper, i.e. quali-quantitative vs. quantitative, as described in Table 2.

For quantitative papers, the following dedicated data were also collected:

1. *Model goal*, i.e. the main goal(s) of the objective function or in general of the approach/model developed in the study;
2. *Model validation*, which is a Y/N field indicating whether the approach used by the authors has also been validated, so that it can be regarded as an accurate representation of the system under study. The validation options proposed by Kleijnen (1995) were taken as a guideline for identifying the possible ways in which a model could have been validated by the authors.

As a general rule, papers were classified using just one option per classification field, assigning them to the category that best reflects the contents of the document; the model goal(s) represent an exception in this regard, as more than one objective could actually be included in the model and all objectives were taken into account in the classification.

2.2.2 Relevant aspects for pandemics risk management

The classification fields highlighted in bold in Table 2 have been introduced to expressively judge the suitability of the risk management models to be used in the case of pandemics, in line with the scope of the paper. These fields are:

- 1) Reference to pandemics risk management → Y: it is self-evident that if a paper has been judged positively as far as this point, the model proposed has potentials to be applied to pandemics, although not necessarily targeting this specific context;
- 2) Disruption type – level 1 → External to the network: pandemic emergencies are disruptions that fall into this classification option, although external disruptions include various types of disturbances. Because of the similarities of these disruptions, it is possible that a model developed for external disruptions could also be adapted to the case of pandemics situations;
- 3) Approach type → Reactive: it is hard to think that the occurrence of pandemics can be prevented, meaning that proactive models, intended to avoid or minimise the occurrence of risks, are probably not suitable to be applied to these situations. Rather, it is expected that models that can be adapted to the case of pandemic situations will fall into the “reactive” category.

Paper type		Classification field	Classification options
Quantitative	Quali-quantitative		
X	X	Main topic	<ul style="list-style-type: none"> • risk • resilience • economics • agility
X	X	Country	<ul style="list-style-type: none"> • single country: the authors carried out the study or applied their model in one single country; • cross-country: the study involved more countries, because of multiple applications/case studies or of empirical research • numerical example: the application is illustrated in the paper, but the authors did not provide details about the country or case study in which the application was carried out, or simply applied the model to a sample case without reference to a real scenario • no application: the authors have not applied their model
X	X	Reference to Industry 4.0	<ul style="list-style-type: none"> • Y: the paper makes use of any of the Industry 4.0 technologies (e.g., big data, cloud computing, digital twin, etc.) • N: otherwise
X	X	Reference to sustainability	<ul style="list-style-type: none"> • Y: the paper mentions sustainability as one of the aims of the study or in general takes it into account inside the model developed • N: otherwise
X	X	Reference to pandemics risk management	<ul style="list-style-type: none"> • Y: the model developed in the paper has been directly applied or has potentials to be applied to the case of pandemics • N: otherwise
X	X	Disruption type – level 1	<ul style="list-style-type: none"> • Internal to the firm • External to the firm but internal to supply chain network • External to the network • Multiple disruption types • Not specified
X	X	Disruption type – level 2	<p>For disruption type “external to the company, internal to the supply chain network”:</p> <ul style="list-style-type: none"> • demand uncertainty • supplier disruptions • multiple disruption types • not specified <p>For disruption type “external to the network”:</p> <ul style="list-style-type: none"> • economic risk (e.g., debt crisis, price instability) • environmental risk (e.g., extreme weather events such as floods, earthquake, tsunami, tornados; climate action failure) • multiple disruption types • geopolitical risk (e.g., terrorist attacks, civil wars) • societal risk (e.g., infectious diseases) • technological risk (e.g., cybersecurity failure, IT infrastructure breakdown) • not specified
X	X	Approach type	<ul style="list-style-type: none"> • Proactive: the model aims at preventing problems before they appear • Reactive: the model focuses on how to respond to disruptions after they have happened

X	X	Model validation	<ul style="list-style-type: none"> Y: the authors applied one of the options suggested by Kleijnen (1995) for validating their model; these options include, among others, the use of empirical data, the development of case studies/multiple case studies, or the usage of experts' opinions; N: the authors have not validated their model
X		Model type - quantitative	<ul style="list-style-type: none"> simulation model / DOE: a parametrized model solved on the computer, coupled with a factorial design of experiments for scenario analysis analytic/mathematical or optimization model: a description of a system using mathematical concepts and language, or a model that aims to optimize (maximize or minimize) an objective function subject to constraints; meta-heuristic or heuristic model: the model makes use of practical approaches to problem solving or self-discovery to solve a problem in a faster and more efficient fashion than traditional methods by sacrificing optimality, accuracy, precision, or completeness for speed; multi-objective optimization model: a mathematical optimization problem involving more than one objective function.
	X	Model type - qualitative	<ul style="list-style-type: none"> fuzzy: the model makes use of fuzzy logic or fuzzy numbers empirical: the study grounds on questionnaire, interviews or case study-based research multi-attribute/multi-criteria decision making: the model developed makes use of MADM or MCDM techniques probabilistic: a probabilistic model grounds on the theory of probability or the fact that randomness plays a role in predicting future events structural equation modelling (SME): SME defines a class of approaches that seek to represent hypotheses about of the means, variances, and co-variances of observed data in terms of a smaller number of 'structural' parameters defined by an underlying theoretical concept (Kaplan, 2001)
X		Model goal	<ul style="list-style-type: none"> Cost: the model aims at minimizing single cost components or the total logistics cost of the system; Profit: the model aims at maximizing the profit of the system; Time: the model aims at minimizing the total supply chain lead time (SCLT) or the total recovery time (TRC) of the system; Efficiency: the model maximizes the productivity, profit/cost ratio or service efficiency; Resilience: the model maximizes system's capability of returning to its original state after being disturbed; Risk: the model minimizes the risk of the system.

Table 2: classification scheme for quali-quantitative and quantitative papers.

3 Results

3.1 Descriptive statistics

The trend in time of the sample of papers reviewed is shown in Figure 1. As this figure shows, the timespan of the publication ranges from 2005 to 2020. In the first years, however, the number of papers published yearly about risk management in the supply chain was quite limited, which is also in line with the fact that the pioneer studies in the field (e.g. Christopher & Peck, 2004) appeared at the

beginning of 2000. A significant increase in the number of papers per year is instead observed starting from 2014 and, since then, the number of publications has always increased in time. The highest number of papers was registered in 2020, which is the possible consequence of the significant impact the COVID-19 pandemics had on supply chains in all their processes (Shokrani et al., 2020).

As far as the publication outlet is concerned, overall the papers reviewed were published in 62 different journals; this denotes that the research field is quite dispersed across different publication outlets and is in line with the fact that risk and resilience are multi-facets and trans-disciplinary topics. Risk, for example, can encompass financial, business or technical aspects, and similarly, resilience is a multi-facet property which includes a number of aspects relating to both internal supply chain processes and external environment (Ivanov & Schönberger, 2019). The variety of aspects involves a wide range of possible journals in which topics relating to risk management can be published. Table 3 lists the 16 journals that published at least two papers belonging to our sample, to provide an idea of the top-journals in the field of risk management. Overall, these journals published 53 out of 99 papers in the sample (53.6%). Interestingly, ten of these journals are indexed in technical subject categories of Scopus, such as either *Mathematics* or *Engineering*; this is consonant with the intended aim of this review, which focuses on technical approaches to risk management.

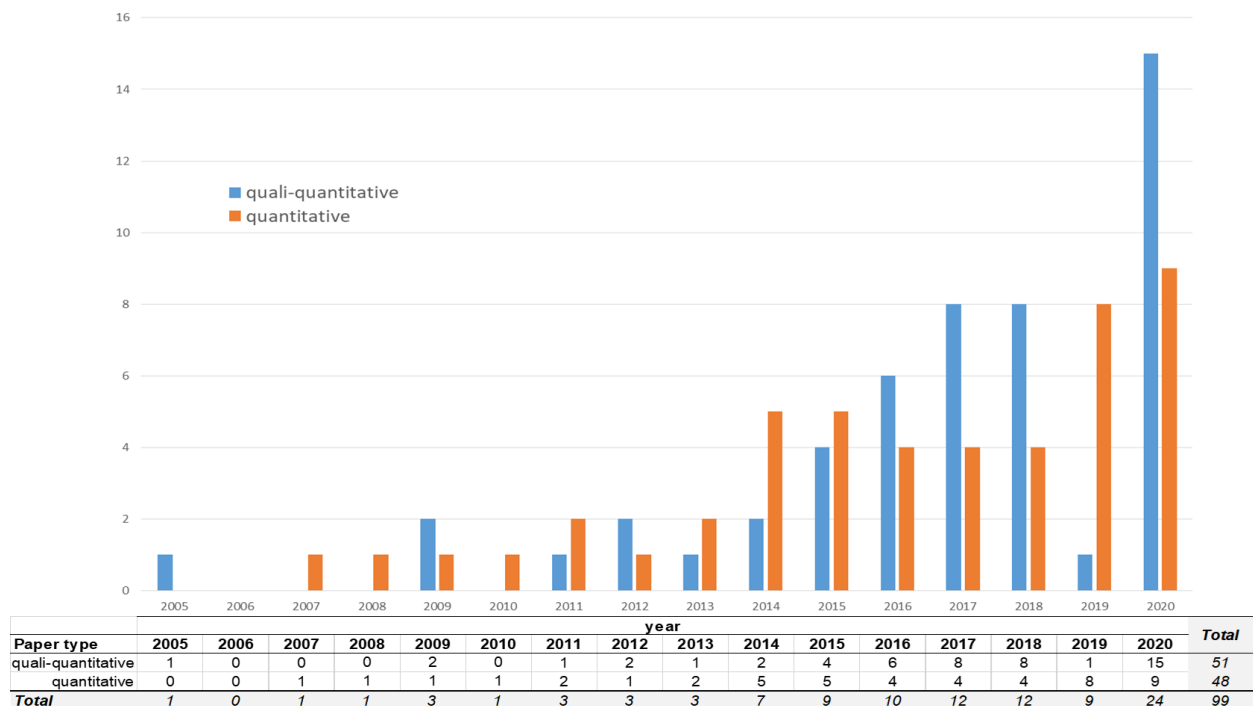


Figure 1: trends of the number of papers in time.

Journal	Paper type		
	quali-quantitative	quantitative	Total
International Journal of Production Research	1	6	7
Supply Chain Management	4	3	7
International Journal of Production Economics	1	5	6
Journal of Cleaner Production	4	1	5
Industrial Management and Data Systems	3	1	4
International Journal of Management Science and Engineering Management	2	1	3
International Journal of Supply Chain Management	3		3
Reliability Engineering and System Safety		2	2
Annals of Operations Research		2	2

International Journal of Physical Distribution and Logistics Management	2		2
European Journal of Operational Research		2	2
Journal of Industrial Engineering and Management	1	1	2
International Journal of Logistics Management	1	1	2
Soft Computing		2	2
International Journal of Operations and Production Management	2		2
Transportation Research Part E: Logistics and Transportation Review		2	2

Table 3: top-journals.

3.2 Common classification fields

3.2.1 Main topics

The papers reviewed cover the main topics proposed in Table 4. In line with the keywords used in the Scopus query, most of the papers (both quantitative and quali-quantitative) focus on risk as the main theme of analysis (55 papers, 56.6% of the studies reviewed). The second most relevant macro-theme is resilience, which is dealt with in 34 papers (34.3% of the sample); it is interesting to note that approximately two thirds of these papers are quantitative, while one third is quali-quantitative. For risk instead, the majority of the papers is of quali-quantitative nature. The last two macro-themes found, i.e. agility and economics, are dealt with in a significantly lower number of papers (7 and 3 respectively). Looking at quali-quantitative studies, papers relating to agility encompass questionnaire surveys (Gunessee et al., 2018), empirical works (L'Hermitte et al., 2016) and structural equation models (Ahmed & Rashdi, 2020); quantitative approaches, instead, include analytic models (Xu and Nozick, 2009) and metaheuristic/heuristic models (Chen & Zhang, 2010). Papers focusing the economic aspect of risk deal typically with the post-disruption economic recovery of systems, either caused by a natural disaster (Zeng et al., 2019) or by the recent COVID-19 emergency (Lutfi et al., 2020; Min et al., 2020).

Main topic	Paper type		Total
	quantitative	quali-quantitative	
Agility	4	3	7
Economics	1	2	3
Resilience	21	13	34
Risk	22	33	55
Total	48	51	99

Table 4: paper type vs. macro-themes.

3.2.2 Disruption type

As far as the disruption types-level 1 (Table 5), 16 papers provided a generic reference to the theme of disruption management but did not expressively indicated the specific disruption taken into account in the study, which prevents the possibility to make a punctual classification. The remaining papers have mainly evaluated disruptions which are external to the company, either internal to the network (33 papers, 32.3% of the sample) or external to the network (27 papers, 27.3% of the sample). A quite relevant number of papers (23) has taken into account multiple disruption types. It is also interesting to note that no papers have dealt with disruptions internal to the company; this is a reasonable consequence of search terms used in the query and denotes that in general the sample of papers correctly focuses on risk in the whole supply chain.

Disruption type	Paper type		Total
	quantitative	quali-quantitative	
external to the company, internal to the supply chain network	21	12	33
external to the supply chain network	9	18	27
multiple disruption types	13	10	23

not specified	5	11	16
Total	48	51	99

Table 5: paper type vs. disruption types – level 1.

Figure 2 shows the second disruption level, thus detailing the previous classification. Looking at disruptions external to the company, both quali-quantitative and quantitative papers mainly focus on supplier disruptions (41% and 47% respectively), followed by multiple disruption types (33% and 28% respectively). Looking instead at the second classification level, many authors have extended the analysis to more than one disruption: 15 quali-quantitative papers and 20 quantitative papers present multi disruption models. Focusing on disruption external to the network, many works deal with environmental disasters (50% and 55% respectively), while other categories have received less attention. It is interesting to underline that among quali-quantitative papers, 4 papers fall into the “societal” risk category, which according to World Economic Forum (2021) includes expressly infectious diseases. Instead, no quantitative papers directly focus on societal risks.

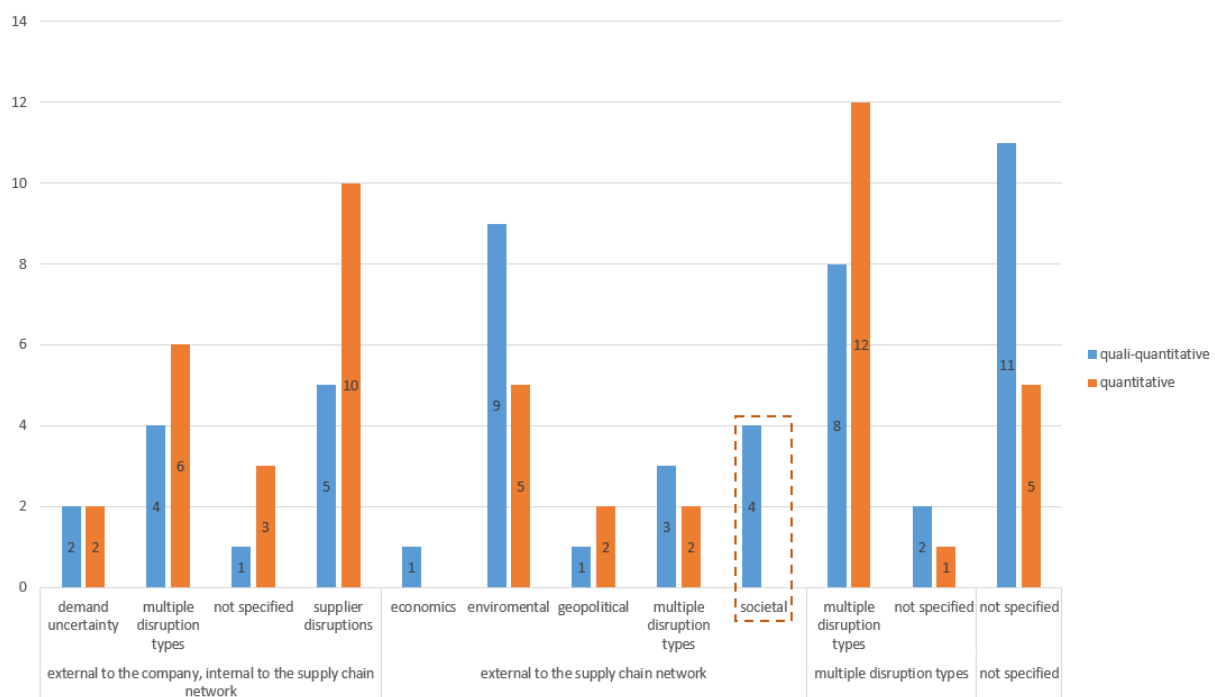


Figure 2: paper type vs. disruption types – levels 1 and 2

3.2.3 Approach type

The approach used by the authors when dealing with risk can be either *proactive*, *reactive* or *mixed* proactive/reactive (Ivanov et al., 2017). For 19 papers reviewed, the exact approach could not be determined (Table 6); this is in particular the case of quali-quantitative studies proposing either questionnaire surveys or structural equations models, whose main goal falls outside the development of specific approaches to counteract risk in the supply chain. The remaining papers are almost equally shared among reactive and proactive approaches to risk management (39 vs. 37 papers respectively). Ivanov et al. (2017) have stressed the ever increasing importance of proactive approaches as resulting from their analysis of the recent literature, for managing the ripple effect of disruptions and effectively designing a resilient system. According to this finding, in our sample the paper dealing with proactive approaches were in fact all written in the last years (from 2012 to 2020).

What is most important to observe is that reactive models are mainly quantitative in nature (28 papers out of 39), while proactive models are mainly quali-quantitative (23 papers out of 37). A possible

justification for this result is that proactive models, being more recent than reactive ones, have less observations and/or data available, which limits the possibility of modelling the scenario in analytic terms as required in quantitative models.

Approach type	Paper type		Total
	quantitative	quali-quantitative	
not specified	3	16	19
post-disruption model (reactive)	28	11	39
pre/post-disruption model (mixed)	3	1	4
pre-disruption model (proactive)	14	23	37
Total	48	51	99

Table 6: paper type vs. approach type.

Further considerations can be drawn from the combination of the approach type and the macro-theme of the study (Table 7). As expected, most of the models focus on resilience and risk as the main topics compared to the remaining macro-themes. Moreover, it is interesting to highlight a possible relationship between the approach type (proactive vs. reactive) and the macro-theme (resilience vs. risk); indeed, reactive models have been mainly proposed when dealing with resilience (18 vs. 15), while proactive models have mainly focused on risk (23 vs. 12). A possible explanation for this outcome is that a proactive model is intended to avoid or minimise the occurrence of risks, which justifies the focus on this specific macro-theme, together with the fact that, when successfully counteracting the occurrence of risks, the whole system will need to be less resilient.

Approach type	Macro-theme				Total
	agility	economics	resilience	risk	
not specified		2	3	14	19
post-disruption model (reactive)	5	1	18	15	39
pre/post-disruption model (mixed)			1	3	4
pre-disruption model (proactive)	2		12	23	37
Total	7	3	34	55	99

Table 7: approach type vs. macro-theme.

3.2.4 Country

For the sake of this paper, “country” denotes the geographical area where the case study (if any) was conducted. In Table 8 the papers describing at least one real-world application (66 papers out of 99) were grouped into the “single country” application category if they targeted a single State/Nation, or into the “cross-country” application category if the study spans across more than one State/Nation. The remaining papers do not present a real-world case study; they were therefore grouped into two sets, i.e. works which proposed an application in the form of a numerical example, but without a geographic location, and papers that do not provide any kind of application.

By correlating this classification with the original distinction between quantitative and quali-quantitative works, it can be observed that the majority of quali-quantitative papers (78.4%) explicitly refer to real national or international supply chains. On the other hand, a significant number of quantitative papers (almost half of the total) did not provide any application or just presented theoretical numerical examples to validate the proposed model. This is probably due to the fact that compared to quali-quantitative approaches, quantitative models need a greater effort for assessing, analysing and interpreting the main assumptions and input data, before being applicable to real-world problems. On the contrary, quali-quantitative studies are mainly focused on empirical data and real case studies (survey, interview or questionnaire), typically carried out in a specific country.

Surprisingly, a very limited number of papers (14 papers out of 99, including quantitative and quali-quantitative) proposes case studies on international supply chains, resulting in a “cross-country” application. This result emphasizes the critical (and not trivial) role of international collaboration, standards and assessments, along with the need for encouraging applied research in this field. Indeed, the potential worldwide impact of today’s supply chain disruptions, though originated in regional territories, has become more and more evident throughout the evolution of the Covid-19 pandemic crisis.

Country	quantitative	quali-quantitative	Total
Single country	34	18	52
Cross-country	6	8	14
No application	8	8	16
Numerical example	3	14	17
Total	51	48	99

Table 8: paper type vs. country.

If limiting the analysis to the 52 papers with a single country application, the geographical distribution of the resulting countries is shown in Figure 3. As this figure shows, the most prolific country appears to be China which slightly exceeds the number of case studies produced in Europe (11 case studies) and in the US (7 case studies). In general, a remarkable attention to supply chain disruptions is evident in areas affected by environmental disruptive events: the Eastern Hemisphere with earthquake, flood or tsunami, and the United states affected by tornados and hurricanes.



Figure 3: geographical distribution of the studies with a single country application.

3.3 Analysis of quali-quantitative papers

3.3.1 Model type

Quali-quantitative papers generally have carried out a risk or resilience assessment using typical qualitative approaches; examples of these approaches are empirical studies supported by statistical analysis, structural equation models (SMEs) or multi-criteria decision making (MCDM) models (Table 9).

Model type – quali-quantitative	Number of papers
Empirical	18
Multi-criteria decision making (MCDM)	13

Structural equation modelling (SME)	12
Fuzzy	4
Probabilistic	4
Total	51

Table 9: classification of the quali-quantitative papers as a function of the model type.

The less frequently used approaches are probabilistic models and fuzzy models. The former models include 4 out of 51 studies (7.8% of the sample) and encompass studies based on Bayesian theory used for addressing risk (Abolghasemi et al., 2015) or resilience management (Yodo and Wang, 2016) by studying relationships among different variables or nodes of the network. Fuzzy models (4 out of 51 studies, 7.8%) instead, have been mainly used for risk identification and assessment; some of them have also included aspects related to Industry 4.0 technologies, with the final aim of ranking risk factors (Dai and Liu, 2020), or of ranking products based on their associated risk (Aqlan, 2016). Again, among fuzzy studies, Niknejad and Petrovic (2016) have tested the propagation of risk in networks using a dynamic fuzzy approach.

Many papers (13 out of 51 studies, 25.4% of the sample) have proposed MCDM approaches for selecting suppliers in a disruptive environment. In such cases, the typical outcome returned by the model is a final suppliers' ranking, which can be obtained on the basis of their risk profile (Khemiri et al., 2017), of risk and sustainability (Zimmer et al., 2017), of the resilience profile (Haldar et al., 2012; Paul, 2015), or of the resilience and green aspects (Rajesh and Ravi, 2015). Other MCDM studies have instead applied multi-criteria analysis for risk evaluation and disruption classification, either by using single techniques (e.g., AHP - Ganguly and Guin, 2013) or combining different techniques, such as AHP and TOPSIS (Rathore et al., 2017), or fuzzy ANP and DEMATEL (Ngan et al., 2020).

Two further wide groups of papers include studies that make use of empirical data coupled with statistical analyses to design the model (Kumar et al., 2018) (18 out of 51 papers, 35.3% of the sample), or coupled with SME (12 out of 51 papers, 23.5%), which has been implemented for studying risk, resilience but also agility and sustainability. In particular, Zineb et al. (2017) have examined the interrelationships between supply chain resilience and flexibility with redundancy and collaboration. Some authors have dealt with modelling supply disruption risk using SME, studying risk perception (Oliveira and Handfield, 2017) or risk propagation (Zhang et al., 2018). The remaining empirical studies include post-disruption analysis on real disruptive events (Hittle & Leonard, 2011) or investigation on SCRM practices (Trkman, 2016). Such papers mainly consist in surveys involving various respondents (Wang et al., 2017), or in interviews with a limited sample of respondents (Durach et al., 2017), or in multiple case studies (Kahiluoto et al., 2020).

3.3.2 Relevance to Industry 4.0 and sustainability

As far as the disruption type is concerned, quali-quantitative papers can be classified considering various levels of detail; Table 10 shows the disruption type-level 1 combined with the relevance to some emerging topics of risk management.

Disruption type	Relevance to other topics		Total
	Sustainability	Industry 4.0	
external to the company, internal to the supply chain network	4	1	5
external to the supply chain network	3	4	7
multiple disruption types	2	5	7
not specified	1	2	3
Total	10	12	22

Table 10: disruption types vs. relevance to other topics for quali-quantitative papers.

A number of authors have analysed disruptions that arise internally to the supply chain but that are external to the company, including green considerations. In particular, these authors have faced the issues of supplier disruptions (Mohammed, 2020) or demand uncertainty (Fierro Hernandez & Haddud, 2018; Sato et al., 2020). Multiple SC disruptions have been considered by Hallikas et al. (2020) to study the relationship between purchasing sustainable practice and SCRM. Others authors have discussed the impact of natural disaster and the effect of different moderating factors (Ali & Gölgeci, 2020).

Among the papers that discuss Industry 4.0 and the general concept of risk, Saleem (2020) tested the potential of Industry 4.0 and the moderating role of automated inventory management systems. Setyawati (2018) has studied the structural relationship between supply chain and risk management, considering the positive role of information technology (IT) in decreasing risk and enhancing the effectiveness of supply chain management. Moreover, some articles focused on multiple disruption types including IT aspects (Jüttner, 2005), while Ekwall (2009) focused on criminal actions and proposed a risk assessment model considering the issue of IT security.

3.3.3 Focus on pandemics risk management

Among the quali-quantitative works, four papers have expressly addressed the topic of pandemic crises and their management. In particular, Kumar (2012) has presented a multiple case study for discussing how different businesses have managed and controlled the avian-flu epidemic. Other studies have expressly debated the COVID-19 pandemic. To be more precise, Min et al. (2020) have discussed the impact of COVID-19 on the food supply chain, while Lutfi et al. (2020) have investigated the effect of social distancing policy on its spread. Belhadi et al. (2021) have provided some results about the destructive effect of pandemic crises on supply chain performance; they have also presented statistics on short/long term response strategies. Besides these studies, thirteen papers, although not specifically dealing with pandemics, have nonetheless found to be somehow related to this topic (Figure 4). For examples, these studies could have dealt with the sanitary sector or focused on a different type of disruption but proposing a model that could be suitable for implementation even for facing a sanitary emergency.

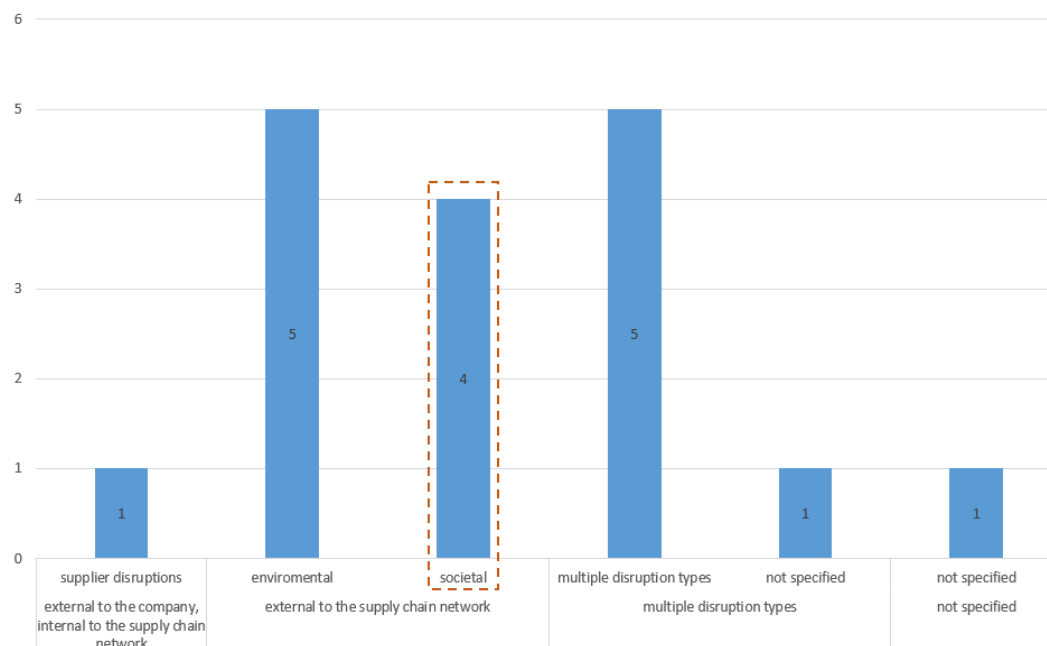


Figure 4: quali-quantitative papers potentially applied to pandemic crises.

Among these studies, Rodgers and Singham (2019) have evaluated the relations between nodes of a clinical supply network and assessed the impact of disruptions along the SC; they have finally determined the vulnerable points of the network. Getele et al. (2018) investigated the effect of social ties, institutional support and inter-agency collaboration in mitigating service supply chain risk in the healthcare sector. A model to help companies to face service emergencies has been proposed by Merz et al. (2009), focusing on critical infrastructure. Badurdeen et al. (2014) have attempted to identify multiple potential risks, including epidemics and diseases, and to assess propagation and interdependencies between them.

The remaining papers do not target the sanitary sector. Nonetheless, the authors have identified and assessed general risk categories, such as catastrophic risk (Er Kara and Firat., 2018), natural disasters (Ma and Wong, 2018), or natural environment risk (Jiang et al., 2017). These kinds of risks have some traits in common with pandemic emergencies, in that they are all due to exogenous factors and somehow unpredictable; these considerations form the basis for judging the models proposed as suitable for a potential application to pandemic emergencies. Otherwise, the studies have evaluated resilience, by presenting either general parameters to assess the level of readiness to disruptions (Sureeyatanapas et al., 2020), or general response/recovery strategies (Chowdhury & Quaddus, 2016), or supplier selection models in a disaster scenario (Haldar et al., 2014). In these models, the same evaluation could be easily carried out including (or adding) pandemic as the disruption type. Moreover, Khayat Basiri et al. (2020) proposed a risk mitigation model, which suggests drivers for measuring and managing pandemic, e.g. the interruption due to the disruption and the duration of the mitigation strategy.

Finally, some papers have studied some specific natural disruptions, which nonetheless present similarities with pandemic emergencies. This is particularly the case for post disruption analyses, in which the authors have evaluated how an extreme event (which could be easily replaced by a pandemic crisis) has affected a system and proposed possible response strategies to risk and adaptation actions (e.g. Jaroszweski et al., 2015; Baharmandet al., 2017).

3.4 Analysis of quantitative papers

3.4.1 Model type

The classification of the 48 quantitative papers according to the model type is shown in Table 11.

Model type – quantitative	Number of papers
analytic/mathematical or optimization	25
simulation model / DOE	11
multi-objective model	7
meta-heuristic or heuristic model	5
Total	48

Table 11: classification of the quantitative papers as a function of the model type.

As can be seen from the table, most of the studies (25 papers out of 48, 52%) have proposed analytic/mathematical models, followed by simulation models (11 papers, 22.9%).

Mathematical models have mainly dealt with risk/resilience management, targeting different topics and goals. A mixed-integer optimization model has been developed by Häntsch & Huchzermeier (2016) with the aim of minimizing the exposure of firms to a general risk. Resilience has been faced in terms of mitigation plans, such as actions for managing supply chain disruptions (Behzadi et al., 2017), models for quantifying the impact of mitigation strategies on disruptive events (Yuan et al., 2020), or proactive policies to mitigate the risk once occurred (Sherwin et al., 2020). Other models have evaluated the

system resilience (Xu et al., 2014) or predicted the point of collapse beyond which the network is unable to reach an acceptable level of performance (Xu et al., 2019).

Simulation models have been developed to analyse different risk scenarios and investigate the impact of disruptive events on supply chains (Berle et al., 2013), testing also specific actions to reduce and mitigate the effect with a focus on risk (Panova & Hilletoft, 2018), resilience (Schmitt & Sing, 2012), or flexibility (Hong, 2015).

Multi-objective models and metaheuristic/heuristic models are less common in the sample of papers retrieved. Among them, Hosnavi et al. (2019) have proposed a model with the twofold purpose of optimizing both risk and resilience, while Paul et al. (2019) have modelled an heuristic procedure to identify a proper recovery plan in line with the disruption type.

3.4.2 Model goal

Correlating the model type with the objective(s) set by the authors in the model itself (Table 12) is useful to identify the approaches which best fit with the specific goal of the analysis. In this respect, Table 12 shows that in general, the minimum cost objective (taken singularly or in combination with other objectives) is pursued by a large part of the studies; this is in line with the fact that building a supply chain which is robust against disruptions is typically expensive (Florin & Linkov, 2016) and makes cost minimization a primary goal of risk management models. For this purpose, Achurra-Gonzalez et al. (2019) have proposed a cost-based mathematical model, which could be used as a decision support tools for the shipping industry to find a suitable routing solution in disruptive scenarios. A system dynamic model has been developed by Bueno-Solano & Cedillo-Campos (2014) to simulate the impact of terroristic acts on the supply chain cost; a reactive mitigation approach has stead been presented by Paul et al. (2018), who also developed an heuristic algorithm for building a cost-based recovery plan after single or multiple disruptions. Finally, Zhao & You (2019) have designed a bi-objective model to simultaneously maximise the system resilience and minimize the supply chain cost.

Model type	Objective					
	Minimum cost	Maximum profit	Minimum time	Maximum efficiency	Maximum resilience	Minimum risk
analytic or mathematical	10	3	3	3	2	4
meta-heuristic or heuristic	4	1				
multi-objective model	5		2		3	4
simulation model / DOE	4	2	4	2	1	
Total	23	6	9	5	6	8

Table 12: model type vs. objective(s).

Interestingly, despite the keywords set in the query, maximizing resilience has been found among the goals of the models in a limited number of cases. Probably, the underlying complexity of risk or resilience, in terms of relationships between decision variables, constraints and assumptions, makes it difficult to clearly model them (Singhal et al., 2011). This is also confirmed by the lack of analytic studies that include maximum resilience among the objectives of the optimization. As far as the analytic models for risk minimization are concerned, they are limited in number as well, in line with the previous finding. These studies approach the minimization of risk in various ways. Adami et al. (2020) have provided a model for identifying the most appropriate redundant strategy to reduce the risk profile of a real supply chain, while Kim et al. (2016) have focused on modelling vulnerability as a measure of supply chain risk and its propagation. The study by Sardar & Lee (2015) instead, has evaluated a very specific topic, i.e. the impact of border crossing bottlenecks on supply chain disruptions.

The second top objective is minimum time: the recovery time is, in fact, an important parameter that certifies the capability of a supply chain to restore its initial condition after disturbances. Munoz & Dunbar (2015) have studied the transient response to disruptions of supply chains, by modelling different resilience dimensions related to time: the recovery time to restore an acceptable performance level, the length of the recovery curve, the severity of the impact along the time, the performance loss from the time of the initial performance reduction, and a time-dependant factor that measures the speed and shape of the transient response. The rationale behind the relevance of these parameters is that if minimizing the recovery time, the service provided to the final customer will be marginally affected by disturbances (Annarelli et al., 2020). Similar considerations hold true for the supply chain lead time. When reconfiguring its structure after a disruption, a supply chain could, for instance, resorting to alternative suppliers, which implies additional lead time; under these circumstances, minimizing the additional lead time (and the total lead time of the system) is a typical objective (Bottani et al., 2019). This consideration is also supported by the fact that most of the studies focusing on time or cost objectives have proposed post-disruption (reactive) models, meaning that the goal of the approach is to restore the normal condition of the system after the occurrence of a disturbance (Table 13). Among these studies, Liberatore & Scaparra (2011) compared different potential protection plans, with the aim of finding the most robust solution for minimizing the impact of disruptive events. Pitty et al. (2008) have tested various policies and responses to disruptions, by evaluating the effect of different decisions on the overall system's economy. Vugrin et al. (2011) have assessed the resilience cost of a particular recovery strategy, taking into account the necessary additional market and transportation costs. Rahman et al. (2018) have combined a proactive approach, to predict in advance the potential system's change, with a reactive mitigation plan, for managing the system during the disruption. Looking at the proactive models, Mari et al. (2019) have developed a supplier selection approach with the aim of simultaneously minimizing cost and lead time, while also maximizing the resilience score, so as to make the system ready to face disruptive situations. Other authors have proposed proactive supplier selection models, combining cost and risk considerations (Fang et al., 2016; Yoon et al., 2018).

Model type	Objective					
	Minimum cost	Maximum profit	Minimum time	Maximum efficiency	Maximum resilience	Minimum risk
pre-disruption model (proactive)	6	2	1	2	2	6
post-disruption model (reactive)	14	3	4	7	3	1
pre/post-disruption model (mixed)	2	1				
not specified	1		1			1
Total	23	6	9	5	6	8

Table 13: approach type vs. objective(s).

3.4.3 Relevance to Industry 4.0 and sustainability

As far as the emerging Industry 4.0 and sustainability topics are concerned, Table 14 shows the correlations between these topics and the type of disruption evaluated by the authors; from this table it is easy to see that most of the quantitative studies focus on disruptions external to the company, but internal to the supply chain.

Disruption type	Relevance to other topics		
	Sustainability	Industry 4.0	Total
external to the company, internal to the supply chain network	3	2	5
external to the supply chain network			-
multiple disruption types		2	2

not specified	2	1	3
Total	5	5	10

Table 14: disruption types vs. relevance to other topics for quantitative papers.

Several papers have targeted specific topics related to Industry 4.0. Examples of these topics include Internet of Things (Yan et al., 2017) or information sharing mechanisms (Li et al., 2007), which are suggested as potential tools for reducing risks in supply chains. Taking a different perspective, Ghadge et al. (2013) have instead evaluated Industry 4.0 as a potential source of risk, as it could involve IT failures and problems associated with hardware/software communication.

Other papers have dealt with sustainability, mainly in terms of green aspects. Among these studies Kaur & Singh (2019) and Li et al. (2020) have proposed sustainable procurement models aimed at minimizing the total cost of a system, including carbon emission costs. Voldrich et al. (2020) have presented a multi-objective model for monitoring cost, time, and risk, with the ultimate aim of optimizing the environmental aspects of the system, such as waste reduction in food supply chains. Finally, Kim et al. (2016) have expanded the concept of risk including all the factors that could have a negative impact on the sustainability of a supply chain.

3.4.4 Focus on pandemics risk management

Thirteen quantitative papers were found to be related to the pandemics risk management, even though no one of these studies has directly targeted this risk (see Figure 5).

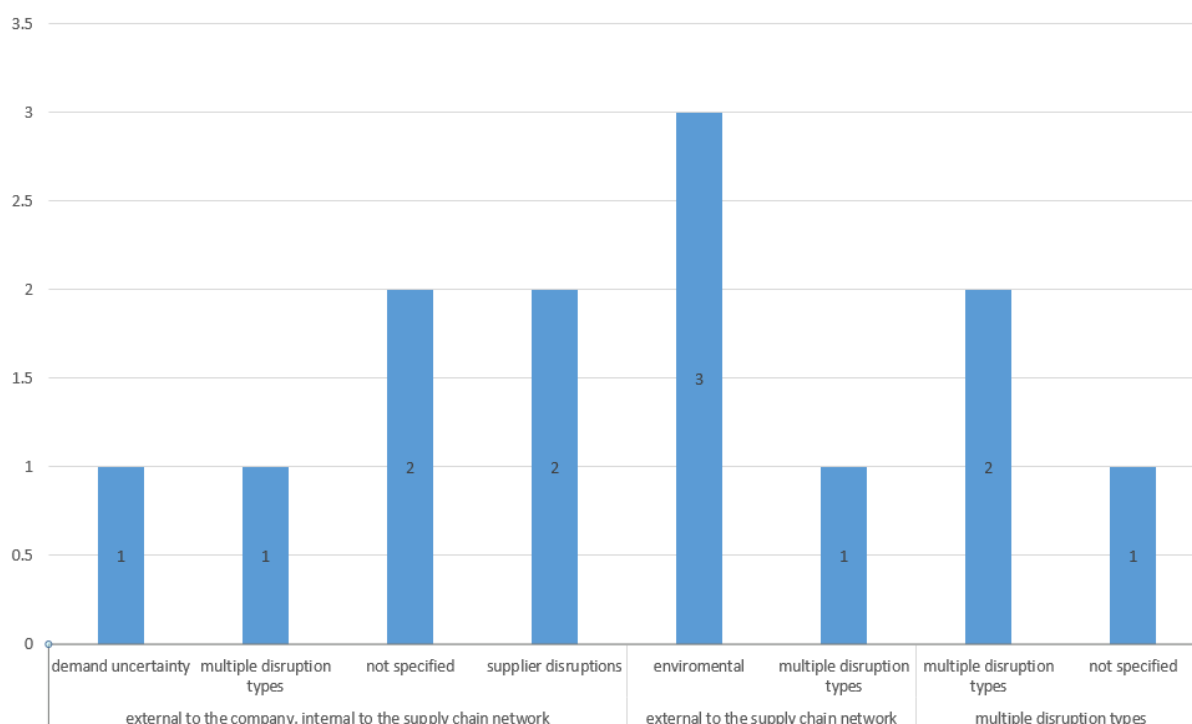


Figure 5: quantitative papers potentially applied to pandemic crises.

The potential link to pandemic risk management stems from various considerations. Some studies target a similar context, as they have proposed general mitigation measures that could be used to manage a sanitary crisis (Paul et al., 2017). Other studies present mitigation plans grounded on Industry 4.0, which could be useful also when managing a pandemic emergency. For example, Micheli et al. (2014) have discussed the adoption of IT systems to share data and therefore reduce the impact of virtually any disruption. Ivanov et al. (2014) have added some considerations related to the

importance of real-time monitoring, with the purpose of increasing visibility along the supply chain and developing quick recovery strategies in collaboration with all supply chain partners.

In some other papers, the focus is on natural disruptions; this risk category owns some characteristics which makes it similar to pandemic emergencies, in that it is due to exogenous and exceptional factors, is almost impossible to predict in its occurrence and is difficult to mitigate. In line with these considerations, models targeting natural disruptions are often adaptable to the management of sanitary crises. Xu & Nozick (2009) have formulated an optimization model in a disruptive environment, testing various scenarios with different natural disruptions; a scenario including a pandemic risk could easily be added to the analysis. Yang & Xu (2015) have investigated the optimal recovery solution to adopt after a natural disruptive event. Geng et al. (2017) have analysed the impact of exceptional events on the import strategies, by evaluating different emergency scenarios.

A number of papers have explored the issue of disruption propagation, which is, once again, a typical characteristics of pandemic emergencies; therefore, the models proposed appear as suitable for application when studying the ripple effect of pandemics (Bogataj et al., 2016). Li & Zobel (2020) have quantified both short-term and long-term behaviours of a system subject to disruptions and its ability to recover the original state; Li et al. (2021) have analysed the forward/backward disruption propagation and its effects on the network. Other papers have paid attention to the resilience assessment, focusing on a crucial aspect of emergency management, i.e. the recovery time needed to react to the disruption. In particular, Raj et al. (2014) have measured resilience quantifying the system response time, while Melnyk et al. (2014) have modelled the transient response of the system. Ahmadian et al. (2020) have presented a model to test and improve the system performance during a disruptive event. Finally, a combination of resilience and sustainability has been proposed by Chatterjee & Layton (2020); these authors balanced redundancy and efficiency for optimizing the network configuration under normal conditions and unexpected events.

4 Discussion, implications and conclusions

This paper has presented a systematic review of the recent literature on risk management and disruptions in the supply chain, with a particular focus on models which are (i) inherently quantitative in nature and (ii) suitable to be applied in the case of a pandemic emergency. The rationale for taking this perspective of analysis, which is quite distant from to existing reviews on SCRM, is twofold. First, the significant and unexpected impact that the COVID-19 emergency has had in recent years on the supply chain has highlighted the need for accurate risk assessment and management approaches. At the same time, however, because of the relative newness of this specific risk, it is hard to believe that models for counteracting the COVID-19 emergency in real supply chains have already been proposed; therefore, the second motivation of this study is to evaluate the SCRM models already available in literature for judging their potential usage in the case of pandemic emergencies.

With this aim in mind, a total of 99 relevant papers, covering the time span between 2005 and 2020 have been reviewed and classified into “quantitative papers”, if a formal mathematical description of the process/system is presented, or “quali-quantitative papers”, if no mathematical/analytic formulae were provided. The two groups of papers have a similar numerosness (51 quali-quantitative papers vs. 48 quantitative papers), suggesting that risk in the supply chain has been studied in literature using various approaches, with a balance between technical tools and less technical ones. As regards the model type, the empirical analysis is the most popular approach among quali-quantitative works, while the majority of quantitative papers propose exact analytical/mathematical models or simulation models.

An interesting outcome of the review is that the trend of publications in time has always increased, with a peak observed in 2020, which is the reasonable consequence of the impact of the COVID-19 pandemics on the SCRM literature. A considerable increase can also be conjectured for year 2021. This is due, first, to the long-term effects of the COVID-19 crisis which, in turn, is expected to exacerbate the impact of other types of global risks in the supply chain (through a “domino” effect), and therefore will certainly fuel additional research in this field. As a second aspect, studies appearing in 2021 could also be the result of the non-negligible time required for reaching the publication stage in peer-reviewed scientific journals, for which the review and publication process may take months or even years.

From the detailed evaluation of the aforementioned 99 papers and by comparing quantitative and quali-quantitative works, the following key considerations can be drawn.

- The most relevant macro-theme addressed is “risk”, treated in the majority of quali-quantitative papers. The second most popular topic is “resilience” which, contrarily to the first macro-theme, is principally dealt with in quantitative papers. This is probably due to the fact that “resilience” is a more defined and circumscribed concept than “risk”, which, on the contrary, is more difficult to model in a quantitative way.
- As opposite to quali-quantitative studies, quantitative papers are more focused on disruptions which are “external to the company but internal to the network”. A possible explanation for this outcome is that this kind of disruptions involves simpler dynamics with respect to those which are instead fully “external to the supply chain network” (and which inherently involve a plethora of complex phenomena). Nonetheless, disruptions “external to the supply chain network” have attracted considerable research interest and form the main focus in most of quali-quantitative papers. Among the disruptions taken into consideration, environmental disruptions (such as natural disasters) are the most investigated ones, while only a limited number of studies (4 papers out of 99) focuses on societal disruptions, which include pandemic emergencies.
- Quantitative papers are more focused on reactive models than on proactive ones. In the authors’ opinion, this outcome should be taken together with the recent proliferation of proactive methods. Indeed, the development of quantitative models generally needs a deeper understanding of the involved phenomena and dynamics, along with (in most cases) the availability of reliable data. This suggests that quantitative proactive approaches can be developed only if an accurate modelling of the system is available, which means that the targeted risk (or a similar one) has been observed several times in its real occurrence, so that its logics can be accurately modelled to allow the disruption event to be forecasted. This could not always be the case for all supply chain disruptions, and in particular is not the case for disruptions which have (likely) occurred a very limited number of times throughout history, such as pandemic emergencies. On the contrary, reactive models, whose logic is to act after a disruption has occurred to restore the system’s functioning, could more easily be based on quantitative approaches, which do not focus on describing the occurrence of the disruption but rather on modelling the system’s recovery.
- It is interesting to note that a noteworthy number of papers describe at least one real-world application. The majority of these works are quali-quantitative papers, while quantitative papers have more frequently been validated through numerical examples. Surprisingly, a limited number of papers only propose case studies targeting international supply chains (labelled as “cross-country” applications), at the same time stressing the need for improving international collaboration, standards and assessments. In general, a remarkable attention to

supply chain disruptions is evident in geographic areas inherently affected by environmental disruptive events, such as the Eastern Hemisphere and the US.

- An increasing, though minor so far, interest towards emerging topics such as Industry 4.0 and sustainability can be observed in the most recent papers (both quantitative and qualitative). It can be noted that works dealing with sustainability are mainly focused on green aspects, leaving the remaining dimensions of sustainability (especially the social one) aside.
- Only four works overall expressly address the topic of pandemic and its management. Moreover, all these works are qualitative-quantitative works; one paper focuses on the avian-flu pandemic, while the remaining three studies deal with the COVID-19 pandemic. In the authors' opinion, further 26 papers of the sample can be potentially applied to pandemic crises, either because of the similarities between the risk analysed and the pandemic emergency, or because they have addressed a general catastrophic event. These papers are almost equally divided into qualitative-quantitative and quantitative works. This outcome emphasizes the need for additional research activities aimed to understand the impact of this specific kind of supply chain disruption and to identify tailored response and recovery strategies. On the other hand, looking at papers judged as suitable for application to pandemic crises has a clear practical implication for companies. Indeed, as recalled, models for counteracting the COVID-19 emergency in real supply chains are still to be built by researchers, because of the newness of the topic. Although it is reasonable to expect that some models will start being developed by the authors in a relatively short time, right now it is paramount for companies to be aware of the available models that, even though not expressly targeting the COVID-19 emergency, could be applied for managing that risk.

Starting from the considerations above, some possible future developments are suggested:

- *Risk measurement and short/long term effects.* In the last years, the effect of catastrophic events on supply chains have been widely studied. Because of the recent epidemic outbreak, researchers have started to study pandemic and its short- and long-term impact on industrial systems. However, qualitative-quantitative models, which measure and analyse the impact of COVID-19 on supply chain performance are still lacking. Moreover, since pandemic is currently underway, a research gap on long-term effects also exists. Because of the lack of data, quantitative models based on pandemics risk management are missing. In fact, quantitative approaches often need a wide set of reliable input data before being applicable to real-world problems. The expected increase in empirical models based on real data and supported by statistical analysis should enhance the opportunity of developing also quantitative models.
- *Risk management, Industry 4.0 and international supply chains.* In a context affected by disruptions, strategies like continuous monitoring, information sharing and real-time data exchange help supply chains to handle the risk. In addition, pandemic has a global spread and involve all the countries, sectors and systems of the world. In this scenario, the collaboration among partners and the visibility along the supply chain become fundamental. Therefore, the adoption of Industry 4.0 technologies is to be regarded as an opportunity to enhance risk management. Currently, a strong research gap has been identified in risk management models that integrate Industry 4.0 and international supply chains. Decision-making models and decision support systems for supply chain risk should integrate the emerging digital technologies and tools, and develop collaborative strategies for “cross-country” systems.
- *Risk management and Sustainability.* Papers that deal with risk management and sustainability are primarily focused on environmental aspects and climate changes. Future studies should

consider all three pillars of sustainability and their implications with risk management, with a particular focus on social sustainability perspective. In fact, epidemics strongly affect people well-being causing significant impacts on society, as demonstrated by the fact that pandemics have been classified into the societal risk category.

- *Resilience and flexibility.* The analysis of the current literature has highlighted a relevant number of models focusing on risk. The second most relevant macro-theme, as mentioned, is resilience, for which a relevant increase has been observed in the last years (16 papers out of 34, i.e. the 47%, have been published starting from 2019). Very few papers, instead, deal with flexibility or agility. However, pandemic is characterized by an inherently variable and unpredictable nature. Hence, systems need an adaptive management in terms of flexibility and ability to react and adapt to changes. Models focused on resilience coupled with flexibility considerations should therefore increase, for capturing the correlations between these aspects.
- *Proactive models and mitigation strategies.* Proactive models have been found to be less numerous than reactive ones. Proactive approaches include studies that aim at reducing the occurrence of risks. In this respect, such approach by itself cannot be directly suitable for application to pandemics risk management, since infectious diseases are almost impossible to be predicted. However, proactive response, restore and recovery strategies should be nonetheless suggested with the aim of mitigating the effects once the disruption occurs. Moreover, the proliferation of proactive strategies aiming at reducing vulnerabilities and enhancing supply chain resilience (e.g. the adoption of multiple suppliers located worldwide) further confirms the importance of cross-country transactions.
- *Ripple effect.* Proactive approaches could also help manage the ripple effect. Due to the particular type of disruption, studies on the ripple effect in global supply chains affected by pandemic are lacking. Two main areas of interest could be explored: the impact of virus propagation on supply chain performance and how an international supply chain could manage different propagation trends across different countries.
- *Infection behaviour along the time.* Another important issue linked to ripple effect is how the infection spreads over time. In fact, compared to other risks due to exogenous factors, pandemic has a unique trait, which makes it strongly different from other catastrophic events. Natural, economic, geopolitical or technological extreme events all have an unexpected nature but they also show an immediate high magnitude, which decreases along the time. On the contrary, pandemic, although always characterised by an unexpected nature, has a different behaviour: it begins with an early stage in which magnitude is limited, followed by an uncontrolled and exponential growth of the effects. Moreover, because of possible multi-wave effects, it is characterized by a sinusoidal trend. No one of the papers reviewed in this study has proposed such type of modelling, which is therefore suggested in future research.

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