Computers & Industrial Engineering 115 (2018) 109–122

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Supply Chain Resilience: Definitions and quantitative modelling approaches – A literature review

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A R T I C L E I N F O

Keywords:
Supply Chain Resilience
Quantitative models
Risk
Literature review
Operations research
Metrics

A B S T R A C T

Resilience is currently an increasing concern in supply chain (SC), caused by their globalization, which is subject to diverse types of disturbances. Such disturbances need to be handled in the right way, compelling the use of tools that can support resilient supply chain decisions. To comprehend how the academic community has been treating such concern we developed a systematic literature review on SC resilience, focusing on the analysis of the development of quantitative methods to support such decisions. A content analysis was performed, in an identified sample of 39 papers, exploiting a solid methodology in the preparation; collection; and analysis of the information obtained. Additionally, published SC resilience definitions were examined and, as result, it was found that there is no consensus in the literature. A sound definition is then proposed, which is supported by a comprehensive framework that includes the four main identified SCR elements: focus event; adaptive framing or adaptive response; speed; performance level. Moreover, it was concluded that the use of quantitative models, although recognised with high relevance in SC resilience, should be further researched as most of the published work explores the conceptualization of only a limited number of resilience elements, lacking the development of integrated holistic approaches. These should simultaneously address the main supply chain characteristics and SC resilience elements. Future directions for the academic community are presented, aiming to guide future research work in the area.

1. Introduction

Supply chain (SC) represent a fairly recent field (Barbosa-Póvoa, 2014). Not that the inherent activities did not exist, but simply were not considered foundations for the organizations. The supply chain management (SCM) concept was, for the first time, identified by Oliver and Webber (1982), and from then on has evolved to meet the challenges brought by the modern economy. With globalization, SCM became a main organizational concern targeting a continuous process of increasing SC efficiency where more complex SC structures need to be optimized for maximum profit under normal circumstances.

The increased size and complexity of supply chain operations leaves decision makers with a large quantity of information, which has been treated in order to be useful, heightening the ability to turn data into quantitative metrics that can be measured and monetarized, Bhagwat and Sharma (2007). Additionally, the SCM scope has been changing not only due to an increase of society's environmental concerns but also due to objectives drawn by economic activities. To meet this new paradigm, supply chain have been shifting from direct flows chain to Closed Loop Supply Chain (CLSC), where not only forward but also reverse flows and activities are considered (Barbosa-Póvoa, 2009; Salema, Barbosa-Povoa, & Novais, 2010). The added complexity of reverse logistics is also the result of strategies created to deal with e-commerce, re-use of products or customer service (Savaskan, Bhattacharya, & Van Wassenhove, 2004). This complexity of flows leads to an increased importance of identifying the right location of individual entities and how they can interact (Farahani, Hekmatfar, Arabani, & Nikbakhsh, 2013; Mota, Gomes, Carvalho, & Barbosa-Povoa, 2015, 2017).

Companies and academics have been involved in a joint effort to deeply develop SC as a whole toward sustainability (Barbosa-Póvoa, Silva, & Carvalho, 2017; Brandenburg, Govindan, Sarkis, & Seuring, 2014; Seuring & Müller, 2008). This leads to the appearance of models and frameworks applied to real case studies, for example, the study of IKEA's Corporate social responsibility in a global supply chain (Lindgreen, Swaen, Maon, Andersen, & Skjoett-Larsen, 2009).

In this changing context, where sustainable globalization is playing an increasing role and where SC are now more exposed to disruptions, SC resilience has emerged. However, it has received little attention, turning this topic underdeveloped, hence creating an opportunity to further studies (Kamalahmadi & Parast, 2016; Tang, 2006). Building

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https://doi.org/10.1016/j.cie.2017.11.006
Received 23 May 2017; Received in revised form 3 November 2017; Accepted 5 November 2017
Available online 07 November 2017

awareness and knowledge regarding SC Risk Management and SC Resilience is an important matter since disruptions, even with low probability of happening, can, if occurring, cause severe impacts on companies. Underestimate or inability to foresee the occurrence and consequences of an event can lead to disruptions with a high impact on SC operations, regardless of SC dimension or direct field of business. Thus, addressing SC resilience is a key factor for a sustainable supply chain advantage.

In this paper, we aim to provide a state of the art on how academics working in SC have been addressing resilience. Two main objectives are pursued: to understand how Supply Chain Resilience has been comprehended by the academic community; and to understand the development made on quantitative methods/models to support complex supply chain decisions when resilience is at stake. A set of research questions was defined where these objectives are explored. A new framework to support a sound SC Resilience analysis is proposed, which results in a comprehensive new SC Resilience definition. The interaction of the risk concept and SC Resilience is analysed as well as the progress on the development of quantitative SC Resilience models. A study on the methods used to build such models, the techniques applied as well as the decision levels treated is presented before addressing SC resilience metrics and strategies. With the new information obtained, research gaps and future directions for SC Resilience are presented aiming to guide future work in the area.

2. Methodology

In order to produce valid work through the literature review, the methodology proposed in Barbosa-Póvoa et al. (2017), is adapted and the following steps are considered: research questions definition; previous literature reviews analysis; material collection; descriptive analysis; category selection and material evaluation. These steps are developed along Sections 3–8.

With this methodology, a new space to obtain and analyse data is available, helping to ensure the viability of the content analysis, without changing the procedures defined and validated in previous works. Coupled with this methodology the bibliometric software *HistCite* was used exploiting the ability to, in a short period, provide several important characteristics of a given set of references (e.g. chronology of the articles or the relationship between the citations of each element).

3. Research questions

Following the motivation of the current paper, described previously, a set of research questions was defined to assess the state of the art on the topic of SC Resilience. These are key to provide a better understanding of the topic and to guide the research to be done. Eight research question where specified:

(1) How resilience has been defined in supply chain?
(2) How resilience and risk have been related in supply chain?
(3) What type of supply chain structure have been considered when addressing resilience?
(4) At what decision level have formal models being developed?
(5) Which operations research methods are most used in modelling Supply Chain Resilience?
(6) Which resilience quantitative metrics have been used?
(7) What kind of risk mitigation strategies have been suggested by the current research?
(8) What challenges still lie for research on resilience in supply chain and which future directions should be taken?

4. Previous literature reviews

The scientific publications here analysed and studied in detail are the result of a search performed on the *Web of Science* database under the terms *"supply chain" AND resilience AND review*. An initial set of 46 publications was identified, which was then refined in order to classify only the Literature Reviews on SC Resilience, resulting in three documents to be analysed:

- Wang, Junwei and Muddada, Raja R and Wang, Hongfeng and Ding, Jinliang and Lin, Yingzi and Liu, Changli and Zhang, Wenjun (2016), Toward a resilient holistic supply chain network system: Concept, review and future direction, IEEE Systems Journal, 10, 2, 410–421
- Kamalahmadi, Masoud and Parast, Mahour Mellat (2015), A review of the literature on the principles of enterprise and Supply Chain Resilience: Major findings and directions for future research, International Journal of Production Economics, 17, 116–133
- Hohenstein, Nils-Ole and Feisel, Edda and Hartmann, Evi and Giunipero, Larry (2015), Research on the phenomenon of Supply Chain Resilience: a systematic review and paths for further investigation, International Journal of Physical Distribution & Logistics Management, 45, 1/2, 90–117

The decision not to consider some publications, at this stage, was performed after a paper content analysis, removing those that did not deal specifically with SC Resilience; were not from peer review journals; or not categorized as reviews. The identified three publications are characterized in Table 1, regarding its objective, research methodology, focus, approach, supply chain relatives, papers analysed and timespan of the publication sample considered. Based on these elements it is possible to infer on the currently published reviews main characteristics and consequently address the pertinence of the current review.

Hohenstein, Feisel, Hartmann, and Giunipero (2015) performed a systematic review on the research development of SC Resilience with a special focus on the conceptualization of SC Resilience, its definition and phases (readiness, response, recovery and growth). A total of 67 publications from years 2003 to 2013 were analysed.

On the systematic review from Kamalahmadi and Parast (2016) 100 publications from the years 2000–2014 are reviewed in order to conclude on the research development on SC Resilience. It develops a framework on the phases of SC Resilience, different from those referred previously (Anticipation, Resistance and Recover & Response) as well as

Table 1
Supply chain resilience reviews characterization.

Paper	Objective	Research Methodology	Papers	Years Analysed	Focus	Approach	SC Relatives
Wang et al. (2016)	Identify and classify SCN and access the state of SC Resilience	Systematic Review	48	1996–2009	SC Network	Qualitative	–
Kamalahmadi and Parast (2016)	Research Development	Systematic Review	100	2000–2014	Organizational and SC Resilience Practices	Qualitative and Quantitative	Uncertainty and Risk
Hohenstein et al. (2015)	Research Development	Systematic Review	67	2003–2013	SC Resilience phases and measurement	Qualitative and Quantitative	Uncertainty and Risk

it considers other formalization on "Supply Chain Resilience Principles". This takes into account the different decision levels, from strategic to operational, and the current reality of supply chain complexity with information assuming a key role when aiming at a resilient operation. An extensive conceptual analysis on SC Resilience is presented, from its definition to the difference between risk and uncertainty, where uncertainty was related to unpredictable events, or in other terms unknown-unknown risks.

Wang et al. (2016) through a Systematic Review of the literature reviewed 48 publications from 1996 to 2009, considering the problematic brought by SC Resilience with emphasis on the behaviour of SC Networks due to its design and organization. The focus on Network Design comes as result of the economic development that leads to bigger and more intricate relationships among several actors, leading to the definition of a *Holistic Supply Chain* to define a "set of SC that are interdependent".

It is noticeable an evolution through time on research for SC and Resilience, with an increase in publications from 2003 and concentrated in regions where the industry is more susceptible to outsourcing risks (Kamalahmadi & Parast, 2016). The chronology is much associated with the terrorist attacks of 9/11 (Hohenstein et al., 2015) that led to a chain of events that caused a disruptive effect in many economic activities. The set of events that followed resulted in a real stress test to the global economy, creating by experience the need to be better prepared for changes in steady state conditions.

From the works above, it can be concluded that a clear definition on SC Resilience is of great importance when sharing knowledge on a global scale. The three publications approached this issue by collecting resilience definitions from several fields, comparing them and ending in a general definition of SC resilience. Due to this importance, the SC Resilience definition topic is further detailed in a specific section in this document. Within such definition, SC Resilience has to be addressed as a set of elements that interact with each other and result in the scenario of disruption or a disturbance to a scenario of normal operation. These elements must be considered in order to aid decision-making process in a disruptive state. Disruptive risks, as well as recovery and reaction strategies, can be categorized on the type of action and thinking it implies (Kamalahmadi & Parast, 2016). Hohenstein et al. (2015) divide the different possible strategies into two categories, proactive or reactive strategies and Wang et al. (2016) adds a third one concerning the anticipation and awareness of events. The authors approach resilience strategies in a rather qualitative manner, providing a set of strategies that can produce results on SC Resilience without providing performance metrics to quantify the impact of a particular strategy on SC operations.

As a conclusion from the analysis of these papers, it can be stated that SC Resilience can hardly be considered as an isolated term, as it is a product of industry and business evolution and needs. For many researchers, it is important to address resilience in combination with complexity, uncertainty and risk.

On the work here presented, we intend to further develop the knowledge on SC Resilience by answering the Research Questions previously defined and differentiating from previous reviews by focusing on the use of quantitative approaches to address SC Resilience. Additionally, a further detail study on SC Resilience definitions is performed proposing a framework to analyse and contextualise SC Resilience definitions in its complexity. To do so a necessary work on the relationship between SC Resilience and Risk, concepts that are often brought up together, was developed.

The remaining of this review is dedicated to the measurement and quantification of SC Resilience, by studying the quantitative models, present in the literature, focusing on the use of Operation Research (OR) methodologies as well as on the strategies and metrics that can be applied in such models.

5. Material collection

Publications here presented and analysed were collected as the result of a set of searches on the *Web of Science* database where the following terms were explored: *"supply chain" AND resilience AND Data Analysis; "supply chain" AND resilience AND Decision Analysis; "supply chain" AND resilience AND Expert Systems; "supply chain" AND resilience AND Heuristics; "supply chain" AND resilience AND Markov Decision; "supply chain" AND resilience AND Meta heuristic; "supply chain" AND resilience AND Neural Networks; "supply chain" AND resilience AND Optimization; "supply chain" AND resilience AND Queuing Theory; "supply chain" AND resilience AND Simulation; "supply chain" AND resilience AND Statistics* and *"supply chain" AND resilience AND Metrics.* This resulted in an initial set of 152 publications.

To better define the papers that should be the focus of further analysis, articles with the following conditions were considered:

- Must be in English language and published in a peer-review journal until December 2016.
- Publications that do not focus on Supply Chain Resilience were excluded.
- Publications regarding non-technical capabilities of Supply Chain Management were excluded.
- Publications with a qualitative approach were excluded.

A content analysis of each paper made possible the intersection with the established conditions and consequently the relevance of each paper was identified. This resulted in a more restricted set of publications, 56 in total, see Table 2. In this set, some publications appear for more than one term of search and then a total of 39 individual publications in a timespan from 2009 until 2016 was acknowledged.

6. Descriptive analysis

One possible method to infer over a particular state is to provide an analysis regarding the factual data, independent from the content of the items. Although limited and forcibly, the information provided by the temporal distribution, geographical distribution and the relative relevance for each paper can be of importance when accessing the current state of the art. These elements are possible to be obtained using HistCite Software. These are shown in Fig. 1A from where it can be concluded that the attention given to this topic is somehow limited geographically, with a higher quantity of publications coming from a restricted set of developed countries or that its economy is dependent on Global Supply Chain, as is the case of India or China.

When considering citations some relevant changes are perceptible. Some publications are responsible for a vast part of the citations and on the other hand, several publications lack citations, consequently have a diminished impact. In Fig. 1B it is observable a weight increase on

Table 2
Results of the initial material collection.

Term	# Initial	# Final
"supply chain" AND resilience AND Data Analysis	26	6
"supply chain" AND resilience AND Decision Analysis	35	13
"supply chain" AND resilience AND Expert Systems	5	1
"supply chain" AND resilience AND Heuristics	4	3
"supply chain" AND resilience AND Markov Decision	0	0
"supply chain" AND resilience AND Meta heuristic	2	1
"supply chain" AND resilience AND Neural Networks	1	0
"supply chain" AND resilience AND Optimization	32	15
"supply chain" AND resilience AND Queuing Theory	0	0
"supply chain" AND resilience AND Simulation	36	13
"supply chain" AND resilience AND Statistics	1	0
"supply chain" AND resilience AND Metrics	10	4
Total	**152**	**56**

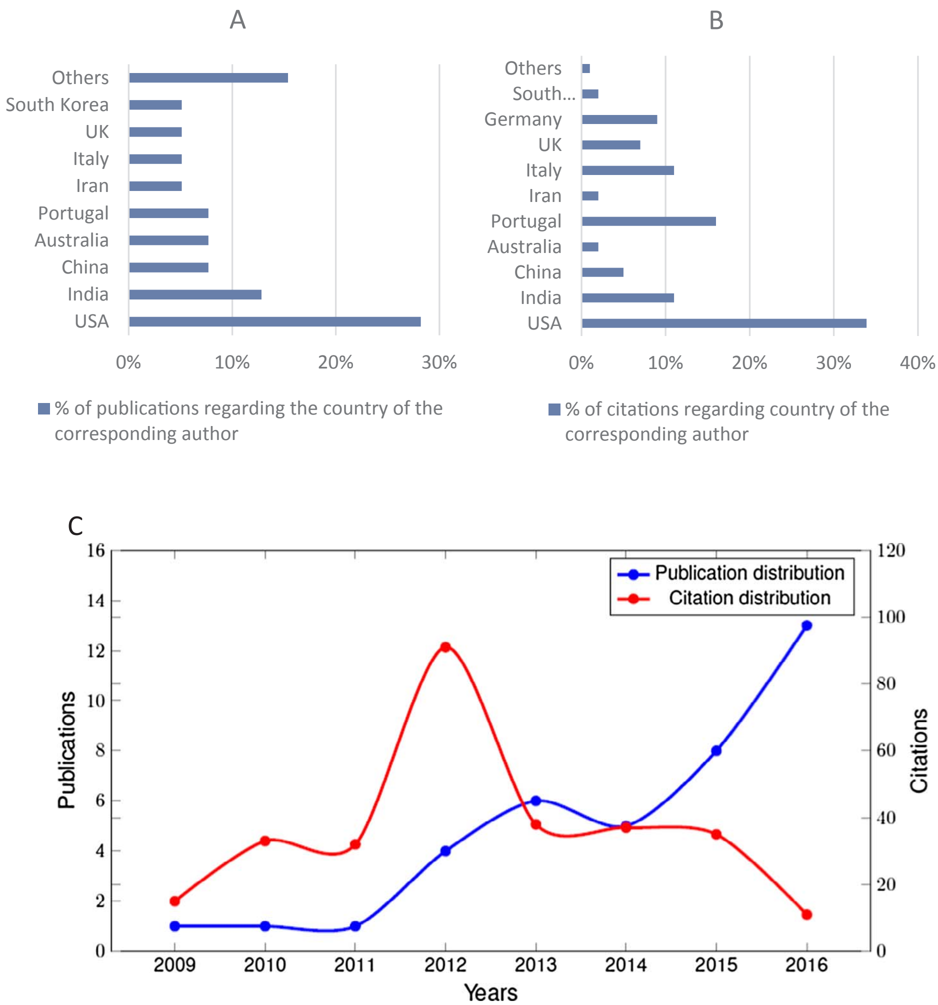

Fig. 1. Distribution of publications characteristics.

publications from Portugal (from 6% of publications, 3 papers, a 16% of citations was obtained) and diminishing citations of publications from Iran, Australia or South Korea. Nevertheless, it should be mentioned that citation analysis is far from being perfect. Two defects from such process can be easily perceived. One comes from the fact that, not always, is being possible to identify negative citations or self-citations (Pilkington & Meredith, 2009) and older papers have a large lifespan to be cited. To some degree, the characteristic identified comes as no surprise, since the countries with decreased impact on citations have publications published in 2016.

It is noticeable from Fig. 1C (Plot in blue) that publications regarding SC Resilience and its quantification are on an incremental path, with 2016 being the year with most identified publications demonstrating the growing awareness regarding Resilience, its quantification and how companies can retrieve competitive advantage from embracing SC Resilience strategies.

Regarding the timeline distribution of citations Fig. 1C (Plot in red[1]), a peak emerges in 2012, just after a period with fewer publications, suggesting that novel work was developed and a benchmark for publications that follow.

The sample here collected is distributed in 25 different Journals, Fig. 2, where a higher number of publications do not mean a higher relevance within the set. Publications are spread through several journals much due to the imprecise definition of resilience (publications on risk or sustainability journals) and the applied nature of many publications drive such publication to be done on specific journals.

Compiling the data from the analysis of publication title makes possible to infer on most recurrent concerns addressed. In Fig. 3 the most common words are listed and besides the expected "Supply" "Chain" and "Resilience", other words are commonly present in titles, such as "Network", "Risk" and "Disruption". These three words are, to some extent, representative of the present state of the art, with resilience being applied in the context of the design of SC Networks, as well as on studies that SC disruptions with risk management.

7. Category selection

Information from the analysed publications must be compatible in order to be possible to retrieve information from a vast set of sources and positively approach the research questions. Publications were listed based on four structural dimensions, Fig. 4: Type of Supply Chain; Decision Level of SCM; Publication Approach; and Model, which includes the OR method used; the existence of resilience metrics; and observed industry.

- Type of Supply Chain: Forward, Closed Loop Supply Chain or Reverse Supply Chain
- Decision Level of SCM: What decision level was addressed in the model? (Strategic, Tactical or Operational?
- Publication Approach: How does the paper approach SC Resilience and how it collects and returns information? (Case Study, Qualitative, Quantitative and eventual description Resilience Strategies)

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

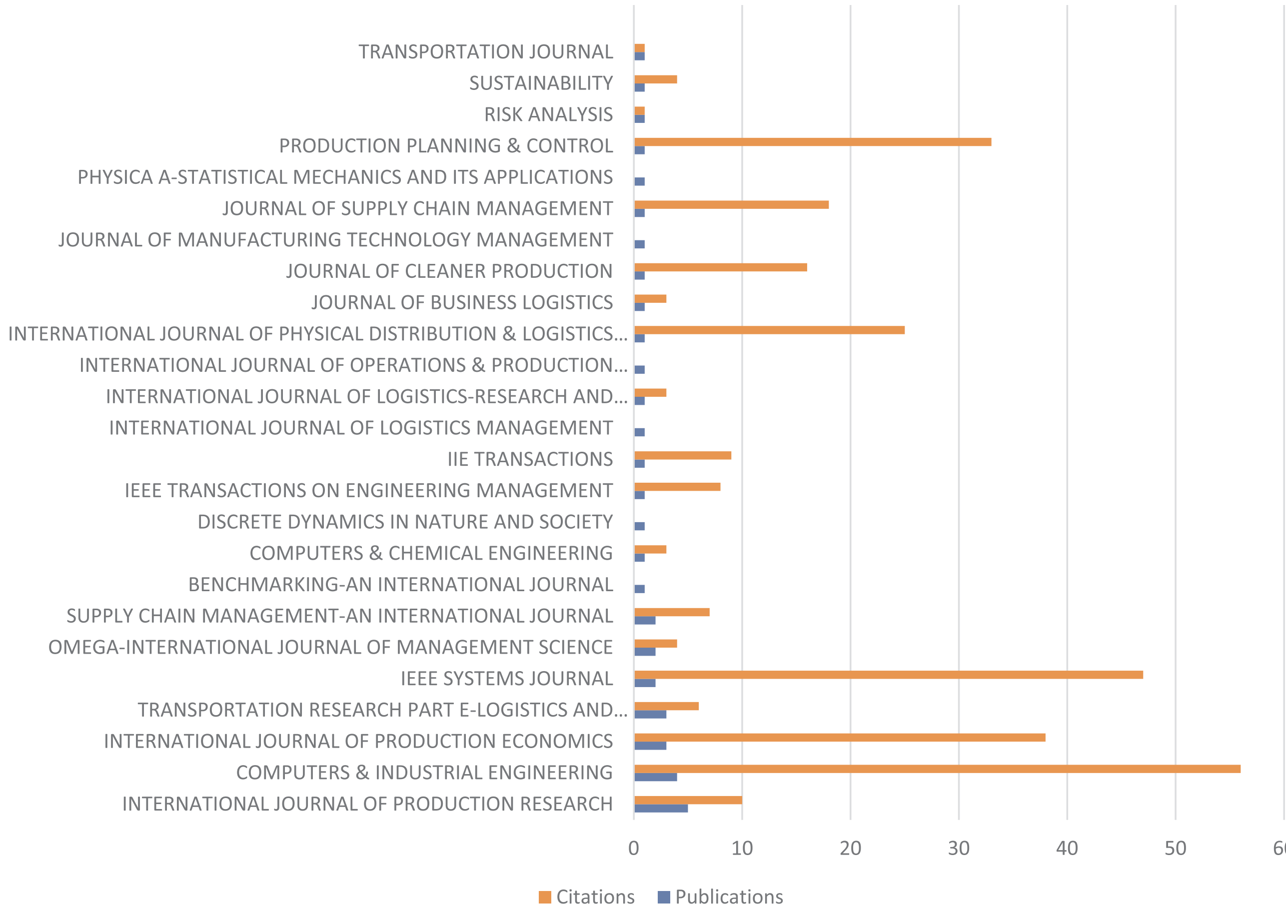

Fig. 2. Journals present in the sample.

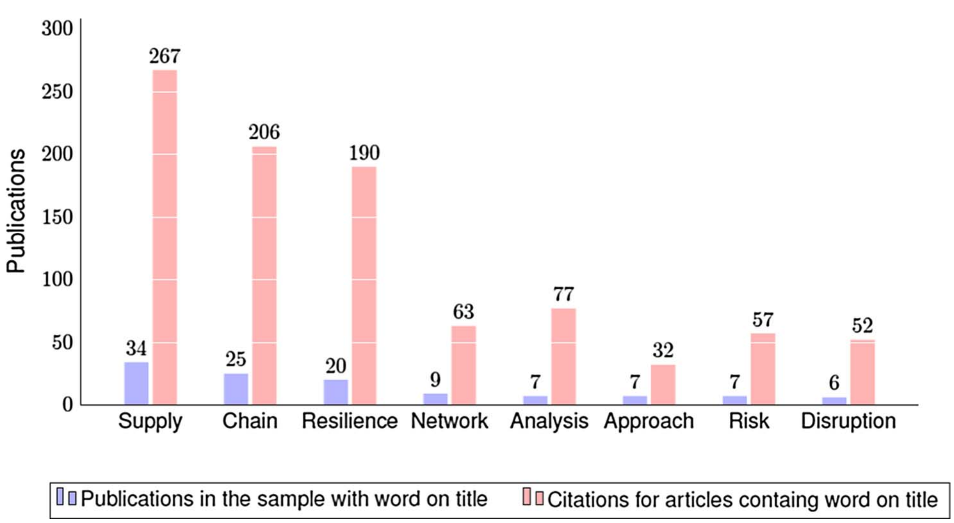

Fig. 3. Word distribution in Title.

- Model: How is the model implemented, considering three dimensions: Operation Research methods used; Resilience Metrics used; and if it looks into a generic example or to a particular industry.

8. Material evaluation

8.1. Supply Chain Resilience definition

(Research Question 1)

The study on SC Resilience definition is crucial to a correct and useful review on a concept that is not yet entirely established, therefore needing a formal and recurrent study.

A primordial approach, to access the present and evolution on SC Resilience definition, is to study the literature available and infer from this the State of the Art. To do that there was a need to create a broader set of publications, including some that were not considered in the final sample. The requisite to add papers from different sources, at this stage, is justified by the fact that these topics are much of a theoretical nature and the publication sample defined is focused on quantitative and applied models. A three steps approach to the collection of SC Resilience definitions is constructed:

Fig. 4. Mind-map for Category Selection.

Table 3
Supply Chain Resilience Definitions – (i).

Authors	Definition	Year
Ponomarov et al.	The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function	2009
Juttner et al.	The apparent ability of some supply chain to recover from inevitable risk events more effectively than others, based on the underlying assumption that not all risk events can be prevented	2011
Roberta Pereira et al.	The capability of supply chain to respond quickly to unexpected events so as to restore operations to the previous performance level or even to a new and better one	2014
Hohenstein et al.	Supply chain resilience is the supply chain's ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance	2015
Junwei Wang et al.	A resilient system is a system with an objective to survive and maintain function even during the course of disruptions, provided with a capability to predict and assess the damage of possible disruptions, and enhanced by the strong awareness of its ever-changing environment and knowledge of the past events, thereby utilizing resilient strategies for defence against the disruptions	2016
Elleuch et al.	Resilience is defined as the ability of a system to return to its original state or a more favourable condition, after being disturbed	2016
Kamalahmadi et al.	The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations	2016

(i) Publications present in the publication sample defined in *Material Collection,* Table 3.
(ii) Publications with relevant content present in the original publication sample defined in Material Collection, that were later excluded from further analysis due to the conditions imposed in *Previous Literature Reviews* or *Material Collection,* Table 4.
(iii) Cross-referencing other publications relevant to the formulation of SC Resilience definition that were not present in any of the original search results, Table 5.

Applying this procedure resulted in a sample of 27 publications, from 2003 to 2016. This will be used in the discussion on SC Resilience definition and on the relationship with Risk.

In a first analysis, it is possible to state that the definition of SC Resilience is not well established and can differ in key elements between different authors and publications. Resilience in SC context has been described in simpler and broader terms by several authors, by implicitly stating that SC Resilience can be described as the ability of the SC to withstand changes of steady-state and converge to the original state or to a new desirable state (Carvalho, Azevedo, & Cruz-Machado, 2012; Christopher & Peck, 2004; Christopher & Rutherford, 2004; Erol, Sauser, & Mansouri, 2010; Rice & Caniato, 2003; Wieland & Marcus Wallenburg, 2013; Xiao, Yu, & Gong, 2012). It is important to clarify that it is not by the complexity or depth of a certain definition that the pertinence of such assertion can be evaluated. The definitions here listed are presented in the context of a particular publication therefore, it is normal the existence of definitions based on the different scientific goals of the original publication.

There are examples of succinct definitions with interesting approaches including elements such as the concept of time in terms of

Table 4
Supply Chain Resilience Definitions – (ii).

Authors	Definition	Year
Geng et al.	Cluster supply chain network suffers from cascading failure when dealing with undesirable disruption, but it can conduct self-repair through adaptability and make it fast recover to a new stable state	2013
Wieland et al.	The ability of a supply chain to cope with change, if its original stable situation is sustained or if a new stable situation is achieved	2013
Berle et al.	The ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission	2013
Brandon-Jones et al.	The ability of a supply chain to return to normal operating performance, within an acceptable period of time, after being disturbed	2014
Birkie et al.	The ability of a business to anticipate, and adapt to sustain and recover operations against disruptions	2016

Table 5
Supply Chain Resilience Definitions – (iii).

Authors	Definition	Year
Rice et al.	The ability to react to unexpected disruptions and restore normal supply network operations	2003
Christopher et al.	The ability of a system to return to its original state or move to a new, more desirable state after being disturbed	2004
Christopher et al.	The ability of a system to return to its original (or desired) state after being disturbed	2004
Closs et al.	The ability to withstand and recover from an incident. A resilient supply chain is proactive—anticipating and establishing planned steps to prevent and respond to incidents. Such supply chain quickly rebuild or re-establish alternative means of operations when the subject of an incident	2004
Gaonkar et al.	The ability to maintain, resume, and restore operations after a disruption	2007
Priya Datta et al.	Not only the ability to maintain control over performance variability in the face of disturbance, but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands	2007
Falasca et al.	The ability of a supply chain system to reduce the probabilities of disruptions, to reduce the consequences of those disruptions, and to reduce the time to recover normal performance	2008
Barroso et al.	The ability to react to the negative effects caused by disturbances that occur at a given moment in order to maintain the supply chain's objectives	2010
Erol et al.	Is a response to unexpected or unforeseen changes and disturbances, and an ability to adapt and respond to such changes	2010
Carvalho et al.	Concerned with the system ability to return to its original state or to a new one, more desirable, after experiencing a disturbance, and avoiding the occurrence of failure modes	2011
Ponis et al.	The ability to proactively plan and design the Supply Chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post event robust state of operations, if possible, more favourable than the one prior to the event, thus gaining competitive advantage	2012
Carvalho et al.	The ability of supply chain to cope with unexpected disturbances	2012
Ponomarov	The adaptive capability of a firm's supply chain to prepare for unexpected events, respond to disruptions, and recover from them in a timely manner by maintaining continuity of operations at the desired level of connectedness and control over structure and function	2012
Xiao et al.	The supply chain's ability of returning to the original or ideal status when this supply chain system has been disturbed by external interruption, and resilient supply chain show abilities on adaptability to environment and recovery	2012
Kim et al.	As a network-level attribute to withstand disruptions that may be triggered at the node or arc level	2015

speed (Brandon-Jones, Squire, Autry, & Petersen, 2014) or chronology position to a disruption or disturbance (Gaonkar & Viswanadham, 2007). The explanation of the goals or performance measures under SC Resilience has not been set in the earliest definitions however, some authors introduce the concept in short definitions (Barroso, Machado, & Machado, 2011; Carvalho, Duarte, & Cruz Machado, 2011; Elleuch, Dafaoui, Elmhamedi, & Chabchoub, 2016). Even in the identified definitions, there is no consensus on the clarification in what are focus events on SC Resilience. “Disruptions”, “Unexpected events”, “Risk Events” or “Disturbances” are terms used to characterize a trigger event that changed the SC from its steady state condition and consequently be the objective of SC Resilience.

More complex and complete definitions, in its majority, are more recent and tend to combine several elements present on earlier and simpler definitions.

In the following Tables, the cited definitions are chronologically listed for the convenience of interpretation and as a reference for the development of upcoming Research Questions.

Considering that the purpose of this work is to advance and create knowledge on the topic, the definition to be used is aimed to be complete and clearly entail the necessary elements for a rigorous but practicable quantitative measure of SC Resilience.

From the analysed literature is possible to purpose a new framework to understand, evaluate and create SC Resilience Definitions. The framework proposed is presented in Fig. 5. It relies on four pillars that should be accounted for: Adaptive Framing or Stage Adaptive Response; Speed; Performance Level; Focus Event.

- Adaptive Framing or Stage Adaptive Response

As described before, there are authors that simply address resilience as the ability to react or to withstand a disruption or disturbance. However, SC Resilience can be seen as a series of adaptive responses in a multi-stage approach regarding the potential events. Closs and McGarrell (2004) take into consideration such elements by stating that a Resilient SC must “withstand and recover from an incident. (…) proactive-anticipating and establishing planned steps to prevent and respond to incidents. (…) quickly rebuild or re-establish alternative means (…)”}. Birkie (2016) suggests a simpler approach on the actions required before, during and after the disruption “Anticipate, and adapt to sustain and recover (…)”. Although a characterization of the elements to face incidents was identified, it misses the awareness on the importance to maintain a steady-state solution after the recovery from a disruption. Ponomarov and Holcomb (2009) propose a definition that accounts for these concerns: “(…) prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations (…)”. The four stages here presented (Prepare, Respond,

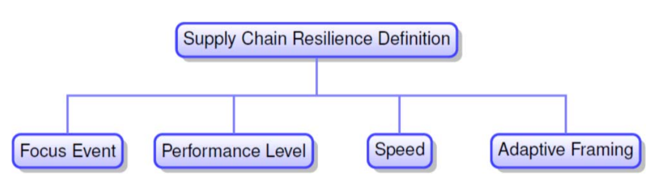

Fig. 5. Mind-map for SC Resilience Definition analysis framework.

Recover and Maintain) are also described in subsequent definitions (Hohenstein et al., 2015; Ponis & Koronis, 2012; Ponomarov, 2012) or in the work presented by Kamalahmadi and Parast (2016) that provided a brief description of the goals for each stage to meet SC Resilience.

It is then crucial that stakeholders involved in SC resilience define the concept and embrace the concern as not being a reaction in a specific individual moment but as a broader concept where the above elements are accounted for. It is therefore important to consider the presence of these elements when analysing SC Resilience definitions.

- Speed

When facing a change that has an impact on the way a firm is operating, producing harm to its results, the time needed to halt such harmful act is of crucial analysis. Closs and McGarrell (2004) introduce the concept of speed in SC Resilience by allowing two possibilities: "(…) quickly rebuild or re-establish alternative means (…)". The concept of urgency in re-establishing steady state is also present in Geng, Xiao, and Xie (2013), Pereira, Christopher, and Lago Da Silva (2014) and Hohenstein et al. (2015) by stating the need for a quick/fast response. Falasca, Zobel, and Cook (2008) and Ponomarov (2012) deal with the time concern with a different approach. They do not apply the word "quick" instead, the concern relies on diminishing the time to recover, in the first, and to simply recover in a "timely manner" in the latter. Ponomorov lists two definitions accounting for time, one from 2009 and the more recent from 2012, with the main difference being the introduction of speed concerns in the SC Resilience definition.

Concluding, it is relevant for SC Resilience definition to include the specific concern regarding the speed on which the system returns to a positive steady state, even if the notion of quick might change depending on the specific case.

- Performance Level

The definition of a certain property should include the concerns that could be the target of evaluation or quantification of such comprehensive definition. Authors have presented, in previous definitions, several elements that can be the root cause to measure resilience.

Falasca et al. (2008) and Kamalahmadi and Parast (2016) address SC Resilience as an adaptive ability to *reduce the probability of disruptions/disturbances*. On the other hand, several authors deal with the period before the disturbance event occurs by referring the efforts on *identifying, anticipating and preparing for events* (Hohenstein et al., 2015; Ponis & Koronis, 2012; Ponomarov, 2012; Ponomarov & Holcomb, 2009; Wang et al., 2016).

Concerning the period when an event, that negatively influences operations, is active, there are key items that can be identified when defining SC Resilience. It is relevant to consider the *consequences and how the system responds to a disturbance* (Falasca et al., 2008; Kamalahmadi & Parast, 2016; Ponomarov, 2012; Ponomarov & Holcomb, 2009; Wang et al., 2016). An objective and simple consideration that can be formulated is related to the ability of the system to *maintain control during the disturbance* (Kamalahmadi & Parast, 2016; Ponis & Koronis, 2012; Ponomarov, 2012; Ponomarov & Holcomb, 2009; Wang et al., 2016) or to sustain the occurrence *without significant impact* (Berle, Norstad, & Asbjørnslett, 2013).

Also, the *time required by the system to return to steady-state* is identified as fundamental when studying the resilience of a particular system (Falasca et al., 2008; Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Pereira et al., 2014; Ponomarov, 2012).

It is then crucial to consider the period consequent to the disturbance and how the system reaches steady state, where a position *equal or better than the original* is relevant for a resilient supply chain (Hohenstein et al., 2015; Pereira et al., 2014; Ponis & Koronis, 2012).

- Focus Event

Several events are associated with SC Resilience. This is a point in definitions that must be clearly identified since it allows for a narrower or broader set of events to influence resilience.

The term *incident* (Closs & McGarrell, 2004) comes as a simpler and broader term in contrast to the most frequent, in the set studied, *Disruption* (Falasca et al., 2008; Hohenstein et al., 2015; Kim, Chen, & Linderman, 2015; Ponis & Koronis, 2012; Ponomarov, 2012; Ponomarov & Holcomb, 2009; Wang et al., 2016). *Disruption,* although the most frequent term, is also the event classification that narrows the set of possible events. It implies that the events that can be the focus of SC Resilience are those that abruptly stop operations completely blocking value creation activities.

Other terms are also used such as: *disturbance* (Kamalahmadi & Parast, 2016; Priya Datta, Christopher, & Allen, 2007); *Unexpected Events* (Ponomarov, 2012; Ponomarov & Holcomb, 2009); and *Risk Events* (Hohenstein et al., 2015; Jüttner & Maklan, 2011). These come as much broader terms that enable SC Resilience to be influenced by simpler events that can produce negative impacts on operations, without disrupting it.

In a matter of fact, the balance between the two perspectives on focus events is perceptible from the fact that several authors (Hohenstein et al., 2015; Ponomarov, 2012; Ponomarov & Holcomb, 2009) include *Disruption* alongside with a broader term.

Being the lack of applied work a concern for many authors, discussed previously in *Previous Literature Reviews*, comes as no surprise the fact that few SC Resilience definitions approach the level of SCM. Ponis and Koronis (2012) and Kim et al. (2015) include such element by suggesting that SC Resilience is a function of the planning and designing of the network concluding that SC Resilience should be addressed on a Strategic Level. Although, relevant to the operationalization of SC Resilience, the strict definition of the decision level involved can be restrictive on the use of a definition.

The term *disturbance* can be presented as a broader term, not only regarding the focus event but also in relation to the different SCM decision levels. It can easily allow for SC Resilience strategies to be applied on a strategic level and on a more operational state.

From the framework analysis, a comprehensive but simple new definition is proposed, resulting from the discussion of the five pillars defined before:

A resilient supply chain should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady state operation in an acceptable cost and time.

8.2. Risk on Supply Chain Resilience

(Research Question 2)

The relationship between Supply Chain and Risk is present in SC Resilience, being this discipline derived from SCRM and SCM (König & Spinler, 2016; Ponomarov & Holcomb, 2009).

Jüttner and Maklan (2011) state that there is an already acknowledged relationship between SC Resilience, Vulnerability (SCV) and SCRM, proposing that the three concepts are complementary for a well-designed SC.

Publications focused on SCRM also address SC Resilience much due to the natural relationship between concepts. For example, Heckmann, Comes, and Nickel (2015) created a framework for SCRM where SC Risk is represented as a primary concept, whereas vulnerability and resilience appear aggregated when it refers to the effects of risk on SC. The two terms appear related, however, a difference in connotation is found. Resilience is perceived with a good connotation, unlike vulnerability that has a negative connotation (Elleuch et al., 2016). Therefore, resilience might be relevant when other concepts fail in empowering firms and academics to study the several elements under risk management.

Following the dogma of considering variability in steady-state conditions as a constant possibility in operations, decisions in SCM can be addressed through the concept of SC Resilience, where a positive impact exists between Risk Management and the need/awareness for investment in resilience (Ponomarov & Holcomb, 2009). This relationship can result in the use of strategies to reduce risk or the consequences related to a particular event (Ponomarov & Holcomb, 2009). However, it is not guaranteed that a risk correction measure would benefit SC Resilience (Jüttner & Maklan, 2011).

One relevant characteristic to be considered is the velocity for a risk event. Jüttner and Maklan (2011) categorize velocity of risk events in three different approaches: the rate that the event happens; the rate that the event fades; how quickly the event is discovered. Then, they propose a newly added factor for velocity regarding SC Resilience: the rate that the SC can recover from a disruption into a new steady-state condition, a concept with increasing impact on SC Resilience definition as discussed in Section 8.1.

Conventional Risk Management relies on the identification and quantification of risk events and consequences, appearing as step-backs when there is no data available in an ever-changing world, thus leading resilience thought as a key process for SCM in handling the risk of an uncertain and complex future (Pettit, Fiksel, & Croxton, 2013). SCRM presents several challenges and insufficient information that disables the traditional methods of managing risk. SC Resilience can provide the tools and knowledge to complement traditional risk management techniques (Kamalahmadi & Parast, 2016). It is this incomplete study, on the interaction between several SC concerns, which generates the need for a greater investment in the study and awareness regarding the several possible approaches for SC Resilience.

The concept *Zone of Balanced Resilience* is proposed by Pettit et al. (2013), as the optimal location for firms to choose. This goal is met by finding an equilibrium between the exposure to risk, and consequent increase in vulnerabilities, and the increasing capabilities that can cause erosion of profits.

Resilience can be seen as an offspring of SCRM and SCV concepts leading to the necessity of addressing such elements in combination (Pereira et al., 2014), revealing that it might not be possible to implement resilience driven actions in an isolated form. Additionally, complex SC, with several tiers, constituted by elements representing several different economic actors, allow partnerships to occur with companies sharing benefits but also risks and creating dependency. This divided stake can, and must, be addressed via resilience strategies that rely on knowledge already created in SCRM.

Concluding and in order to address resilience, companies must be aware of their exposure to risk, which implies a continuous Risk Analysis and Assessment (Ponomarov & Holcomb, 2009).

8.3. Supply Chain Resilience Quantitative Models and SCM decision level

(Research Questions 3, 4 and 5)

SC Resilience quantitative models are a fairly new effort for academics and practitioners, appearing as a consequence of the growing concern on SC Resilience. With the growth in knowledge, quantitative models went in consonance with the concepts discussed, adding particular relevance to the SC Resilience definition endorsed.

Models must define its scope and one relevant measure for scope is the level of the decision within the SCM framework. When the distribution of the decision level is analysed, Fig. 6A, it provides a simple and effective way to analyse at what decision level models have been aiming to. Strategic decisions are the most common, with SC Resilience being a property of the network as a whole. Therefore, consequences on SC Resilience quantification come from upper levels of decision. The intricate relationship to tactical decisions leads to most of the authors to consider tactical factors synchronized with strategic concerns.

The OR methods present in the different publications, Fig. 6B, are concentrated in three main modelling approaches: Optimization, Simulation and Decision Analysis. This distribution reflects the preferred methods to quantify SC Resilience, with models that can provide easy construction and understanding being those that decision makers can trust with ease. Models are getting more complex keeping up with the consolidation of SC Resilience concepts and relevance to SC operations.

From the set of 39 publications, a high number of models apply some kind of numeric confirmation, most in form of a case study (24 Publications). From the set of papers that deploy a model on a case study, it is not possible to identify any prominent field of application, with nine publications not identifying specifically the industry of the presented example. It is possible to identify some models that focus on the same industry as, for example, the case of aeronautics or the retail industry, with two representative cases each, and electronics with three examples (Rajesh & Ravi, 2015a, 2015b; Rajesh, Ravi, & Venkata Rao, 2015). Using case studies is the preferred method to test the model with real-life scenarios and it can provide information to meet its objectives and ultimately aid decision making on improving SC Resilience. With SC dealing with great distances and minimal time objectives aircrafts are often used to fulfil such objective. Wang and Ip (2009) deal with SC Network Resilience applied to the field of Aircraft Service, crucial for continuous flow of aircrafts, by quantifying resilience as dependent on Demand and Supply, with its redundant possibilities, thus simplifying quantification and interpretation. However, reducing the variability of inputs that real life systems suffer. Thekdi and Santos (2015) propose a model regarding the specific context of port operations where interdependence of different infrastructure and the risk of operations disruptions are measured, reaching suggestions regarding decision making under several types of disruption scenarios. Maritime transport disruptions are also addressed by Berle et al. (2013) with a Monte Carlo simulation with quantity delivered being the performance metric for comparison.

Authors proceed with different approaches on the construction of quantitative models, much depending on its goals regarding the scope, depth and application of the model. Harrison, Houm, Thomas, and Craighead (2013) create a simple model where it optimizes a SC network by iteratively removing a node from the SC and re-optimize the remaining structure thus being possible to create several disruptions scenarios. Contrasting from simple models, Hasani and Khosrojerdi (2016) create a fairly complex, but complete, model combining classic OR methods with Heuristics in order to study network design under uncertainty applying resilience strategies to the context of global SC. There are approaches on the specific concern of inventory management and disruptions caused by stock-outs. Boone, Craighead, Hanna, and Nair (2013) provides a case study where inventory is managed under a system approach rather than focusing on individual items and Spiegler et al. (2016) proposes an elaborated non-linear model, with objective to control inventory and reduce stock-out situations, representing the dynamic relationship between errors of knowledge, variability and eventual inventory disruptions. There are simulation models to study resilience in terms of inventory stock-out at three levels of analysis (customer, retailer and manufacturer) taking also into consideration the customer behaviour and its impact. Wu, Huang, Blackhurst, Zhang, and Wang (2013) propose an agent-based simulation model and Schmitt and Singh (2012) not only implement a simulation model for the case study at hand but also proposes a set of strategies to mitigate the consequences of inventory stock-out.

It is perceptible a concern regarding the sustainability of SC in several published works. For instance, Fahimnia and Jabbarzadeh (2016) and Mari, Lee, and Memon (2014) study the impact of green SC to SC Resilience, creating a multi-criteria model combining Environmental and Social performance score with SC Cost under a set of disruption scenarios recurring to a goal programming approach to compare the conflicting objectives. In their work, there is sustained evidence that allows for the possibility of achieving a "*resiliently sustainable SC*".

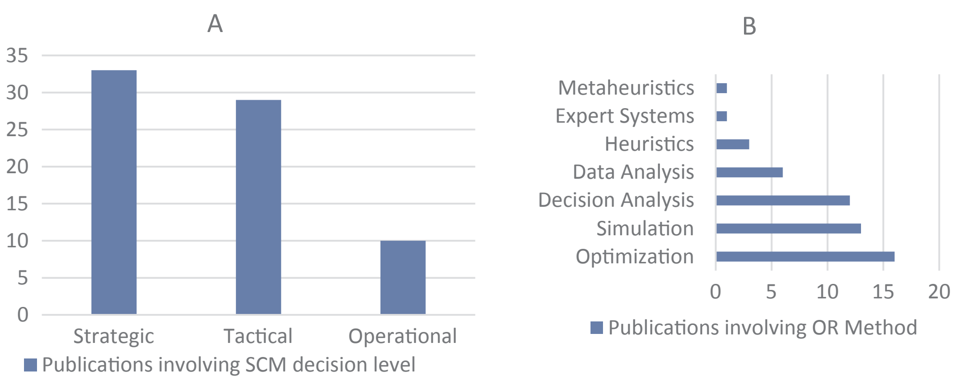

Fig. 6. Model characteristics distribution.

Lean practices take on as a more usual principle for operations and Birkie (2016) uses Bayesian Networks on the consequences of integrating lean and resilience strategies on system performance under disruptions, concluding that Lean is not a constraint for resilience practices implementation.

8.4. Strategies and Metrics applied in Supply Chain Resilience Quantitative Models

(Research Questions 6 and 7)

SC Resilience Strategies and Metrics vary as authors and objectives change. This is made clear in Table 6, where the set of factors that are explicitly applied to SC Resilience are summarized.

From our research, only three publications (Azevedo, Carvalho, & Cruz-Machado, 2016; Soni, Jain, & Kumar, 2014; Wang & Ip, 2009) quantify SC Resilience in a Single Index, using a set of 21 factors to measure Resilience goals of a particular SC, Factors R_i in Table 6. Most of the identified publications tend to incorporate SC Resilience factors in the models, being those factors crucial for results interpretations, but do not aim at creating a SC Resilience Index. From the identified set of papers, it is possible to extract 48 Resilience Factors, Factors F_j in Table 6, which the different authors apply in order to provide better information regarding SC Resilience.

Analysing the papers that propose a single index, it is interesting to see that the work by Wang and Ip (2009) departs from a study of an Aircraft service. The authors access, in this operation, the most relevant metrics and establish a resilience metric for each node involved and provide a network resilience metric by performing a weighted sum of each node resilience. Soni et al. (2014) create an Index to measure and compare SC Resilience. This relies on several enablers of resilience, which were identified via a survey with practitioners and academics. From the identified enablers, a study on its interdependence is presented through a matrix involving 10 chosen enablers. More recently, Azevedo et al. (2016) propose an index to classify SC in a combination of four vectors (Lean, Agile, Resilient and Green), presenting a set of resilience metrics and its relative weights to SC Resilience. An automotive SC is studied.

When analysing that papers that incorporate SC Resilience factors into the models developed but not aiming at a single index several papers were identified, where it can be seen the diversity of factors considered (see Table 6, Factors F_j). Zhao, Kumar, Harrison, and Yen (2011) address the network design problem using a simulation approach. The authors analyse the obtained results recurring to three resilience new metrics (availability, connectivity and accessibility) and propose a new approach to resilient SC Design based on a military hierarchy. Adenso-Diaz, Mena, García-Carbajal, and Liechty (2012) deal with reliability on SC and look into the SC network design problem. A Monte Carlo simulation model is developed considering thirteen factors that influence reliability, while identifying its relative importance in a particular case. Brandon-Jones et al. (2014) study the SC supply-side by considering visibility as a key capability. The authors justify such importance through an empirical evidence by developing a survey to practitioners, and a consequent data analysis on the measure of several parameters (SC connectivity, information sharing, SC visibility and geographic dispersion). SC Resilience is assumed as a result of the *restoration of material flow and operating performance, recovery of the supply chain, and the speed with which disruptions would be dealt with*. As main conclusion, the authors state that supplier selection should be performed taking into consideration the resilience capabilities of the involved entities. Munoz and Dunbar (2015), recurring to Structural Equation Modelling (SEM), create a model to quantify resilience characterizing the response to a disruption of the system performance over time, visually and with a rationale associated (five Dimensions: *Recovery time*, *Impact*, *Profile Length*, *Performance Loss* and *Weighted Sum*). For the first time, Cardoso, Barbosa-Póvoa, Relvas, and Novais (2015) study the design and planning of a CLSC developing an optimization model where 11 indicators to measure SC Resilience are proposed. Such indicators are grouped into two main types: Network design; and Operational indicators. The CLSC characteristics expressed into the network design indicators denote the level of resilience achieved among different CLSC networks. Using a survey with practitioners Hosseini and Barker (2016) create a Bayesian Network model to assist in the decision where resilience is a structural element characterized by a set of seven criteria related to the resilience of suppliers (see Table 6: F40 to F46). Finally, Resilience is also a subject for models with concise and simple performance measures such as the model formulated by Dixit, Seshadrinath, and Tiwari (2016) where *Percentage of unfilled demand* and *Total transportation cost* post-disaster are seen as fundamental.

As resilience is a concept with ambiguity on its definition, it is expected to find resilience quantification on models not identified with SC Resilience indicators, as are the publications that are to be referred next. There are models that do not comprehensively present a set of quantitative metrics with the goal to address SC Resilience, rather they present models that contain, what we now can infer as, resilience concerns, not providing enough information to replicate the quantification of such concern. Therefore, these publications are not present in the previous table providing, however, relevant information, that is analysed next. This is the case of Han and Shin (2016) that created a model that analyses resilience by measuring robustness including the concepts of risk propagation after a disruptive event, taking into consideration not only risk but also network configuration. Nooraie and Parast (2016) provide a model to study the relationship between SC Risk Drivers, investment and consequence costs when applying SC Resilience strategies, by studying the overall maximization of revenues and minimization of costs. Sokolov, Ivanov, Dolgui, and Pavlov (2016) propose a model assuming SC Design as the focus of analysis with the interaction of a static model (Network Constants) and a dynamic model (Variable under uncertainty) with Service Level and Delivery Reliability as performance indicators. Wieland and Marcus Wallenburg (2013)

Table 6
Resilience factors present in models to quantify SC Resilience.

Paper	Factors
Wang and Ip (2009)	*Resilience for each node* R1: Supply Reliability R2: Edge Reliability R3: Factor between (Demand, Supply and transport capacity) and demand *Network Resilience* R4: Weighted sum of each node resilience
Soni et al. (2014)	R5: Sustainability R6: Risk and revenue sharing R7: Trust R8: Visibility R9: Risk management culture R10: Adaptive capability R11: Structure
Azevedo et al. (2016)	R12: sourcing strategies to allow switching of suppliers R13: flexible supply base/flexible sourcing R14: strategic stock R15: lead time reduction R16: creating total supply chain visibility R17: flexible transportation R18: developing visibility to a clear view of own stream inventories and demand conditions R19: Agility R20: Collaboration R21: Information Sharing
Zhao et al. (2011)	F1: Availability: percentage of demand nodes that have access to supply nodes F2: Connectivity: Size of the largest functional sub-network F3: Accessibility: Maximum supply path length and average supply-path length
Adenso-Diaz et al. (2012)	F4: Node Complexity F5: Suppliers Complexity F6: Sources Criticality F7: Density F8: Variance Density F9: Node Criticality F10: Flow Complexity F11: Node Reliability F12: Flow Reliability F13: Cluster Reliability F14: Variance Node Reliability F15: Variance Flow Reliability F16: Variance Cluster Reliability
Brandon-Jones et al. (2014)	F17: SC Connectivity F18: Information Sharing F19: SC Visibility F20: SC Resilience F21: SC Robustness F22: Environmental Dynamism F23: Scale Complexity F24: Differentiation F25: Delivery Complexity
Munoz and Dunbar (2015)	F26: Recovery F27: Impact F28: Performance Loss F29: Profile Length F30: Weighted Sum of F26 to F29
Cardoso et al. (2015)	Network Design F31: Node Complexity F32: Flow Complexity F33: Density F34: Node Criticality Network Centralization F35: Quantity of inbound and outbound flows F36: Intensity of inbound and outbound flows Operational F37: Expected Net Present Value F38: Expected Customer Service Level F39: Investment
Hosseini and Barker (2016)	F40: Geographical Segregation F41: Surplus Inventory F42: Backup Supplier Contracting F43: Physical Protection F44: Rerouting F45: Restoration Budget F46: Technical Resource Restoration
Dixit et al. (2016)	F47: Percentage of unfulfilled demand post-disaster F48: Total transportation cost post-disaster

create a model involving a survey of practitioners with the main objective of measuring the SC Customer Value due to resilience, assuming it in two dimensions (Agility and Robustness). Taking into consideration resilience concerns, Carvalho, Azevedo, and Cruz-Machado (2012), Carvalho, Barroso, Machado, Azevedo, and Cruz-Machado (2012) elaborate a simulation model applied to SC Network Design in the context of automotive industry, correcting "Supply delay" as the main goal, analysing Lead Time and Total Cost as performance measures. Sadghiani, Torabi, and Sahebjamnia (2015) perceives total system cost seen as fundamental for the analysis of disruptive scenarios. Under the above publications, the objective function commonly addresses the minimization of SC Costs/maximization of Net Present Value, under a more or less elaborated set of variables considering a set of disruption scenarios. However, Ehlen, Sun, Pepple, Eidson, and Jones (2014) create a model where the objective function is to minimize a sum of two penalizing terms (Deviation of optimal state and Producing or consuming products with no actual demand). Geng et al. (2013) and Wang and Xiao (2016) propose a model to address SC Resilience on SC that is keen to cascade failures, due to internal or external factors. The authors conclude that the cooperative and inherent relationships between several players naturally leads to having the capability of flexibility with the latter presenting the model based on ant colonies. Rajesh and Ravi (2015a) and Rajesh et al. (2015) study the cause-effect relationships of enablers of SC Risk Mitigation (15 identified enablers) in a three-step model (Grey-DEMATEL). The work resulted in the identification of a set of strategies that represent the highest significance in the model (*Dynamic Assortment Planning, Accurate Demand Forecasting, Supply Chain Visibility, Collaborative Partner Relations and Integrated Supply Chain*). Rajesh and Ravi (2015b) use Grey Theory to address the action of choosing suppliers, considering 13 attributes relevant for resilient SC, divided into four groups of factors (*Primary performance factors, Supplier's responsiveness, Supplier's risk reduction, Supplier's technical support, Supplier's sustainability*). With the objective of identifying bundles/portfolios of strategies to better cope with SC disruptions, Chowdhury and Quaddus (2015) list a set of vulnerability factors, SC Resilience capabilities and its dependency culminating in the listing of strategies to meet the issues identified. However, the determination process for the resilience value is through a weight and expected capacity to mitigate disruptions.

Upstream disruptions are a particular disruptive event and can be understood as a concern regarding the supply side of a Supply Chain. Gualandris and Kalchschmidt (2015) focus on the interaction between risk management, disruptive events and competitive advantage via a misfit analysis, trying to establish a balanced-resilience logic. The referred misfit was measured based on a Euclidian distance between the experimental unit and a risk profile taking into consideration not only risk conditions but also the implementation of mitigation practices. Dabhilkar, Birkie, and Kaulio (2016) address supply-side resilience performing a case-study analysis of actual disruptions and interviews stakeholders involved, creating a link between qualitative to quantitative through statistical analysis creating 4 bundles of resilience practices (from the interaction of Proactive-Reactive and Internal-External practices), concluding that such groups are complementary. Saghafian and Van Oyen (2012) produces a particular work on the supply side, analysing the introduction of a *secondary flexible backup supplier* to compensate any fluctuation in production in case of disruption, the model created does not quantify resilience *per si*, being the financial indicator, “money that a risk-neutral firm should be willing to invest to implement” one of the two strategies at stake: Value of *Generalized capacity reservation* and the value of analysis suppliers to enhance awareness of disruption risks, the final comparative element.

Global supply chain not only creates a supply chain with an increased number of agents but also it can increase distances between origin and destination. This paradigm takes lead times to a concept that cannot be ignored. Colicchia, Dallari, and Melacini (2010) study such element on SC using a hub and spoke system. They implement a simulation model and identify contingency plans, mitigation actions as well as vulnerabilities that endanger the successful accomplishment of activities. Azadeh, Atrchin, Salehi, and Shojaei (2014) studies the effects of flexibility, redundancy, velocity and visibility in face of SC Disruptions by using simulation and Fuzzy Data Envelopment Analysis (FDEA) to create a method to order individual, or groups of, resilience practices, applied to different scenarios characterized by a particular state (pessimistic, most likely, optimistic).

9. Research gaps and future directions

From the literature analysed it can be stated that the scientific field of SC Resilience is on a positive path with more knowledge and applications being developed recently. This is advancing SC Resilience and its applicability to real-life situations. Regardless, further research is needed, which should follow some important directions, as below discussed.

The recurrent need for the extensive characterization of the term *Resilience* in a SC context comes from the inexistence of a clear definition of SC Resilience, which can be used in different possible contexts. At the current stage of research, the work already done with such objective is significant. However, further developments are required to consolidate the work already performed on SC Resilience definition. Researchers should converge to a stable SC Resilience definition, embracing the fact that SC Resilience is an aggregating concept, involving expertise already created on other fields of SCM, such as Risk Management. In this paper, we have proposed a new definition that encompasses the different concerns listed and discussed in the analysed papers.

Within the analysed literature, a relationship between risk and resilience is perceptible when considering a chronological evolution. SC Resilience comes as the latter term, appearing as an aggregation term allowing further development in the specific field. Classical Risk management can be seen as a procedure to mitigate the low impact and frequent risks, often neglecting high impact risks as is the case of low probability disruptions (Li & Gulati, 2015). Resilience awareness can mitigate such neglect and the combination of such concepts should than be further researched.

As seen in this paper, SC Resilience is a concern that is relevant for SC operations and consequently for economic activity. Modern complex SC represent a greater set of elements, interactions and intricate flows, with many of these networks representing a global operation. The ability to acquire knowledge of already implemented strategies to cope with such kind of scenarios is of greater importance. The complexity of real-life systems is something still to be explored. Quantitative models can help in this study and can act as tools to aid the implementation of resilience practices, providing the necessary insight to acknowledge requirements, objectives and consequences. However, this area is not yet fully explored, thus investment on the development of quantitative models should be done in order to measure comprehensively SC Resilience, not focusing on a concrete part of a SC operation but adopting a global view. It is crucial that new OR methods are implemented, exploring the development of artificial intelligence like the deployment of Expert Systems supported by optimization tools. Created models are often limited as they often fail to represent reality. Thus, the creation of more holistic models regarding complex SC that incorporate reverse flows and account for the SC resilience elements is essential. The integration of different OR methods should also be explored, as for instance decision analysis methods combined with optimization would allow the translation of qualitative concepts, often present in SC resilience problems, into quantified forms that can be tackled by optimization.

The construction of more realistic models may lead to an increase in complexity, which can reveal difficulties in their solution. Thus, the research community should explore the development of faster alternative solution methods such as meta-heuristics.

Within the models, performance metrics assume a key role. However, these are only appropriate if they accurately measure the transient results along several tiers of the SC in different disruptive scenarios. This is still an area in need of further research due to its relevance when applying SC Resilience models in real decision making, as it ultimately allows an increased knowledge on the complete SC functioning.

Additionally, developing efforts on SC Resilience strategies at the different SC decision levels to mitigate the lack of strategies focusing on the operational level is also a path to follow, that should be covered in future models.

Finally, the treatment of real cases should be further explored as, although most of the papers claim to have dealt with case studies, the current state of the art does not provide nor a vast and broad spectrum nor a particular investment of an individual industry in SC Resilience quantitative models. Therefore, moving to meet such gap is imperative.

10. Conclusion

In this paper, a systematic literature review was performed, aiming to identify the existent definitions of Supply Chain Resilience and to understand the development progress of quantitative models to support SC Resilience decisions. This is a topic of growing interest for academics and practitioners, however, from our research, only three publications were identified as reviews on the SC resilience and none of them was focused on the use of quantitative models. Our paper contributes to reducing such gap.

We start by presenting a study on SC Resilience definition, identifying the different authors’ approaches and conceptualizations proposed. This lead to the development of a novel framework, that translates the pertinence and scope of SC Resilience and supports a new, proposed, sound definition for SC Resilience, which can meet the current and future challenges.

Additionally, a content analysis was performed on quantitative SC Resilience models in a set of 39 publications, retrieving with special relevance resilience metrics, OR methods and SCM decision level addressed.

From the work developed, it can be stated that the implementation of resilience practices can be one efficient and important strategy for enterprises to create competitive advantage. Also, the relationship between resilience concerns and risk events was acknowledged.

The use of quantitative models to support decisions when building and operating resilient supply chain was shown to be prominent and a set of challenges was presented to further develop and implement SC Resilience using quantitative models. A clear need for the improvement of decision-making tools so as to provide better and trustworthy information to decision makers was identified, which can only be achieved by developing more comprehensive quantitative models that represent real scenarios, including SC with reverse flows, and make use of effective OR methods.

SC Resilience is, in conclusion, a field of study that can have a positive impact on companies, needing more thorough studies so as to meet the identified challenges and explore the potential of such interesting field.

Acknowledgments

The authors acknowledge the Portuguese National Science Foundation (FCT): project PEst-OE/MAT/UI0297/2011 and Direccion General de Investigacion Cientifica y Tecnica: project CIMADISC.

References

Adenso-Diaz, B., Mena, C., García-Carbajal, S., & Liechty, M. (2012). The impact of supply network characteristics on reliability. *Supply Chain Management: An International Journal, 17*(3), 263–276.

Azadeh, A., Atrchin, N., Salehi, V., & Shojaei, H. (2014). Modelling and improvement of supply chain with imprecise transportation delays and resilience factors. *International Journal of Logistics Research and Applications, 17*(4), 269–282.

Azevedo, S. G., Carvalho, H., & Cruz-Machado, V. (2016). LARG index: A benchmarking tool for improving the leanness, agility, resilience and greenness of the automotive supply chain. *Benchmarking: An International Journal, 23*(6), 1472–1499.

Barbosa-Póvoa, A. P. (2009). Sustainable supply chains: Key challenges. *Computer Aided Chemical Engineering, 27*, 127–132.

Barbosa-Póvoa, A. P. (2014). Process supply chains management – Where are we? Where to go next? *Frontiers in Energy Research, 2*, 23. http://dx.doi.org/10.3389/fenrg.2014.00023.

Barbosa-Póvoa, A. P., Silva, C., & Carvalho, A. (2017). Opportunities and challenges in sustainable supply chain: An operations research perspective. *European Journal of Operations Research*. http://dx.doi.org/10.1016/j.ejor.2017.10.036.

Barroso, A. P., Machado, V. C., & Machado, V. H. (2011). *Supply chain resilience using the mapping approach.* INTECH Open Access Publisher.

Berle, Ø., Norstad, I., & Asbjørnslett, B. E. (2013). Optimization, risk assessment and resilience in LNG transportation systems. *Supply Chain Management: An International Journal, 18*(3), 253–264.

Bhagwat, R., & Sharma, M. K. (2007). Performance measurement of supply chain management: A balanced scorecard approach. *Computers & Industrial Engineering, 53*(1), 43–62. http://dx.doi.org/10.1016/j.cie.2007.04.001.

Birkie, S. E. (2016). Operational resilience and lean: In search of synergies and trade-offs. *Journal of Manufacturing Technology Management, 27*(2), 185–207.

Boone, C. A., Craighead, C. W., Hanna, J. B., & Nair, A. (2013). Implementation of a system approach for enhanced supply chain continuity and resiliency: A longitudinal study. *Journal of Business Logistics, 34*(3), 222–235.

Brandenburg, M., Govindan, K., Sarkis, J., & Seuring, S. (2014). Quantitative models for sustainable supply chain management: Developments and directions. *European Journal of Operational Research, 233*(2), 299–312.

Brandon-Jones, E., Squire, B., Autry, C. W., & Petersen, K. J. (2014). A contingent resource-based perspective of supply chain resilience and robustness. *Journal of Supply Chain Management, 50*(3), 55–73.

Cardoso, S. R., Barbosa-Póvoa, A. P., Relvas, S., & Novais, A. Q. (2015). Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty. *Omega, 56*, 53–73.

Carvalho, H., Azevedo, S. G., & Cruz-Machado, V. (2012). Agile and resilient approaches to supply chain management: Influence on performance and competitiveness. *Logistics Research, 4*(1–2), 49–62.

Carvalho, H., Barroso, A. P., Machado, V. H., Azevedo, S., & Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Computers & Industrial Engineering, 62*(1), 329–341.

Carvalho, H., Duarte, S., & Cruz Machado, V. (2011). Lean, agile, resilient and green: Divergencies and synergies. *International Journal of Lean Six Sigma, 2*(2), 151–179.

Chowdhury, M. M. H., & Quaddus, M. A. (2015). A multiple objective optimization based QFD approach for efficient resilient strategies to mitigate supply chain vulnerabilities: The case of garment industry of Bangladesh. *Omega, 57*, 5–21.

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *The International Journal of Logistics Management, 15*(2), 1–14.

Christopher, M., & Rutherford, C. (2004). Creating supply chain resilience through agile six sigma. *Critical Eye, 24*, 28.

Closs, D. J., & McGarrell, E. F. (2004). *Enhancing security throughout the supply chain.* DC: IBM Center for the Business of Government Washington.

Colicchia, C., Dallari, F., & Melacini, M. (2010). Increasing supply chain resilience in a global sourcing context. *Production Planning & Control, 21*(7), 680–694.

Dabhilkar, M., Birkie, S. E., & Kaulio, M. (2016). Supply-side resilience as practice bundles: A critical incident study. *International Journal of Operations & Production Management, 36*(8), 948–970.

Dixit, V., Seshadrinath, N., & Tiwari, M. K. (2016). Performance measures based optimization of supply chain network resilience: A NSGA-II + Co-Kriging approach. *Computers & Industrial Engineering, 93*, 205–214.

Ehlen, M. A., Sun, A. C., Pepple, M. A., Eidson, E. D., & Jones, B. S. (2014). Chemical supply chain modeling for analysis of homeland security events. *Computers & Chemical Engineering, 60*, 102–111.

Elleuch, H., Dafaoui, E., Elmhamedi, A., & Chabchoub, H. (2016). Resilience and vulnerability in supply chain: Literature review. *IFAC-Papers OnLine, 49*(12), 1448–1453.

Erol, O., Sauser, B. J., & Mansouri, M. (2010). A framework for investigation into extended enterprise resilience. *Enterprise Information Systems, 4*(2), 111–136.

Fahimnia, B., & Jabbarzadeh, A. (2016). Marrying supply chain sustainability and resilience: A match made in heaven. *Transportation Research Part E: Logistics and Transportation Review, 91*, 306–324.

Falasca, M., Zobel, C. W., & Cook, D. (2008). A decision support framework to assess supply chain resilience. In *Proceedings of the 5th international ISCRAM conference* (pp. 596–605).

Farahani, R. Z., Hekmatfar, M., Arabani, A. B., & Nikbakhsh, E. (2013). Hub location problems: A review of models, classification, solution techniques, and applications. *Computers & Industrial Engineering, 64*(4), 1096–1109. http://dx.doi.org/10.1016/j.cie.2013.01.012.

Gaonkar, R. S., & Viswanadham, N. (2007). Analytical framework for the management of risk in supply chains. *IEEE Transactions on Automation Science and Engineering, 4*(2), 265–273.

Geng, L., Xiao, R., & Xie, S. (2013). Research on self-organization in resilient recovery of cluster supply chains. *Discrete Dynamics in Nature and Society*, 2013.

Gualandris, J., & Kalchschmidt, M. (2015). Supply risk management and competitive advantage: A misfit model. *The International Journal of Logistics Management, 26*(3), 459–478.

Han, J., & Shin, K. (2016). Evaluation mechanism for structural robustness of supply chain considering disruption propagation. *International Journal of Production Research, 54*(1), 135–151.

Harrison, T. P., Houm, P. J., Thomas, D. J., & Craighead, C. W. (2013). Supply chain disruptions are inevitable – get READI: Resiliency enhancement analysis via deletion and insertion. *Transportation Journal, 52*(2), 264–276.

Hasani, A., & Khosrojerdi, A. (2016). Robust global supply chain network design under disruption and uncertainty considering resilience strategies: A parallel memetic algorithm for a real-life case study. *Transportation Research Part E: Logistics and Transportation Review, 87*, 20–52.

Heckmann, I., Comes, T., & Nickel, S. (2015). A critical review on supply chain risk–Definition, measure and modeling. *Omega, 52*, 119–132.

Hohenstein, N.-O., Feisel, E., Hartmann, E., & Giunipero, L. (2015). Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation. *International Journal of Physical Distribution & Logistics Management, 45*(1/2), 90–117.

Hosseini, S., & Barker, K. (2016). A Bayesian network model for resilience-based supplier selection. *International Journal of Production Economics, 180*, 68–87.

Jüttner, U., & Maklan, S. (2011). Supply chain resilience in the global financial crisis: An empirical study. *Supply Chain Management: An International Journal, 16*(4), 246–259.

Kamalahmadi, M., & Parast, M. M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics, 171*, 116–133.

Kim, Y., Chen, Y.-S., & Linderman, K. (2015). Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management, 33*, 43–59.

König, A., & Spinler, S. (2016). The effect of logistics outsourcing on the supply chain vulnerability of shippers: Development of a conceptual risk management framework. *The International Journal of Logistics Management, 27*(1), 122–141.

Li, Z. & Gulati, R. K. (2015). Supply chain risk mitigation and the application potential of complex systems approaches. In *Proceedings of the 18th Asia pacific symposium on intelligent and evolutionary systems*. Vol 1 (pp. 357–371).

Lindgreen, A., Swaen, V., Maon, F., Andersen, M., & Skjoett-Larsen, T. (2009). Corporate social responsibility in global supply chains. *Supply Chain Management: An International Journal, 14*(2), 75–86.

Mari, S. I., Lee, Y. H., & Memon, M. S. (2014). Sustainable and resilient supply chain network design under disruption risks. *Sustainability, 6*(10), 6666–6686.

Mota, B., Gomes, M. I., Carvalho, A., & Barbosa-Povoa, A. P. (2015). Towards supply chain sustainability: Economic, environmental and social design and planning. *Journal of Cleaner Production, 105*, 14–27.

Mota, B., Gomes, M. I., Carvalho, A., & Barbosa-Povoa, A. P. (2017). Sustainable supply chains: An integrated modeling approach under uncertainty. *Omega*.

Munoz, A., & Dunbar, M. (2015). On the quantification of operational supply chain resilience. *International Journal of Production Research, 53*(22), 6736–6751.

Nooraie, S. V., & Parast, M. M. (2016). Mitigating supply chain disruptions through the assessment of trade-offs among risks, costs and investments in capabilities. *International Journal of Production Economics, 171*, 8–21.

Oliver, R. K., Webber, M. D., et al. (1982). Supply-chain management: Logistics catches up with strategy. *Outlook, 5*(1), 42–47.

Pereira, C. R., Christopher, M., & Lago Da Silva, A. (2014). Achieving supply chain resilience: The role of procurement. *Supply Chain Management: An International Journal, 19*(5/6), 626–642.

Pettit, T. J., Fiksel, J., & Croxton, K. L. (2013). Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics, 31*(1), 1–21.

Pilkington, A., & Meredith, J. (2009). The evolution of the intellectual structure of operations management 1980–2006: A citation⧹co-citation analysis. *Journal of Operations Management, 27*(3), 185–202.

Ponis, S. T., & Koronis, E. (2012). Supply chain resilience: Definition of concept and its formative elements. *Journal of Applied Business Research, 28*(5), 921.

Ponomarov, S. (2012). Antecedents and consequences of supply chain resilience: A dynamic capabilities perspective.

Ponomarov, S. Y., & Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. *The International Journal of Logistics Management, 20*(1), 124–143.

Priya Datta, P., Christopher, M., & Allen, P. (2007). Agent-based modelling of complex production/distribution systems to improve resilience. *International Journal of Logistics Research and Applications, 10*(3), 187–203.

Rajesh, R., & Ravi, V. (2015a). Modeling enablers of supply chain risk mitigation in electronic supply chains: A Grey-DEMATEL approach. *Computers & Industrial Engineering, 87*, 126–139.

Rajesh, R., & Ravi, V. (2015b). Supplier selection in resilient supply chains: A grey relational analysis approach. *Journal of Cleaner Production, 86*, 343–359.

Rajesh, R., Ravi, V., & Venkata Rao, R. (2015). Selection of risk mitigation strategy in

electronic supply chains using grey theory and digraph-matrix approaches. *International Journal of Production Research, 53*(1), 238–257.
Rice, J. B. & Caniato, F. (2003). Building a secure and resilient supply network. *Supply Chain Management Review.* Vol. 7(5) (Sept./Oct. 2003), pp. 22–30: Ill.
Sadghiani, N. S., Torabi, S. A., & Sahebjamnia, N. (2015). Retail supply chain network design under operational and disruption risks. *Transportation Research Part E: Logistics and Transportation Review, 75*, 95–114.
Saghafian, S., & Van Oyen, M. P. (2012). The value of flexible backup suppliers and disruption risk information: Newsvendor analysis with recourse. *IIE Transactions, 44*(10), 834–867.
Salema, M. I. G., Barbosa-Povoa, A. P., & Novais, A. Q. (2010). Simultaneous design and planning of supply chains with reverse flows: A generic modelling framework. *European Journal of Operational Research, 203*(2), 336–349.
Savaskan, R. C., Bhattacharya, S., & Van Wassenhove, L. N. (2004). Closed-loop supply chain models with product remanufacturing. *Management Science, 50*(2), 239–252.
Schmitt, A. J., & Singh, M. (2012). A quantitative analysis of disruption risk in a multi-echelon supply chain. *International Journal of Production Economics, 139*(1), 22–32.
Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production, 16*(15), 1699–1710.
Sokolov, B., Ivanov, D., Dolgui, A., & Pavlov, A. (2016). Structural quantification of the ripple effect in the supply chain. *International Journal of Production Research, 54*(1), 152–169.
Soni, U., Jain, V., & Kumar, S. (2014). Measuring supply chain resilience using a deterministic modeling approach. *Computers & Industrial Engineering, 74*, 11–25.
Spiegler, V. L. M., Potter, A. T., Naim, M. M., & Towill, D. R. (2016). The value of nonlinear control theory in investigating the underlying dynamics and resilience of a grocery supply chain. *International Journal of Production Research, 54*(1), 265–286.
Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics, 103*(2), 451–488.
Thekdi, S. A., & Santos, J. R. (2015). Supply chain vulnerability analysis using scenario-based input-output modeling: Application to port operations. *Risk Analysis*.
Wang, D., & Ip, W. H. (2009). Evaluation and analysis of logistic network resilience with application to aircraft servicing. *IEEE Systems Journal, 3*(2), 166–173.
Wang, J., Muddada, R. R., Wang, H., Ding, J., Lin, Y., Liu, C., & Zhang, W. (2016). Toward a resilient holistic supply chain network system: Concept, review and future direction. *IEEE Systems Journal, 10*(2), 410–421.
Wang, Y., & Xiao, R. (2016). An ant colony based resilience approach to cascading failures in cluster supply network. *Physica A: Statistical Mechanics and its Applications, 462*, 150–166.
Wieland, A., & Marcus Wallenburg, C. (2013). The influence of relational competencies on supply chain resilience: a relational view. *International Journal of Physical Distribution & Logistics Management, 43*(4), 300–320.
Wu, T., Huang, S., Blackhurst, J., Zhang, X., & Wang, S. (2013). Supply chain risk management: An agent-based simulation to study the impact of retail stockouts. *IEEE Transactions on Engineering Management, 60*(4), 676–686.
Xiao, R., Yu, T., & Gong, X. (2012). Modeling and simulation of ant colony's labor division with constraints for task allocation of resilient supply chains. *International Journal on Artificial Intelligence Tools, 21*(3), 1240014.
Zhao, K., Kumar, A., Harrison, T. P., & Yen, J. (2011). Analyzing the resilience of complex supply network topologies against random and targeted disruptions. *IEEE Systems Journal, 5*(1), 28–39.