



Review

A critical review on supply chain risk – Definition, measure and modeling[☆]



Iris Heckmann^{a,*}, Tina Comes^b, Stefan Nickel^{a,c}

^a Department of Logistics and Supply Chain Optimization, Research Center for Information Technology (FZI), Karlsruhe, Germany

^b Centre for Integrated Emergency Management, University of Agder (UiA), Grimstad, Norway

^c Institute for Operations Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

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ABSTRACT

Economic systems are increasingly prone to complexity and uncertainty. Therefore, making well-informed decisions requires risk analysis, control and mitigation. In some areas such as finance, insurance, crisis management and health care, the importance of considering risk is largely acknowledged and well-elaborated, yet rather heterogeneous concepts and approaches for risk management have been developed. The increased frequency and the severe consequences of past supply chain disruptions have resulted in an increasing interest in risk. This development has led to the adoption of the risk concepts, terminologies and methods from related fields. In this paper, existing approaches for quantitative supply chain risk management are reviewed by setting the focus on the definition of supply chain risk and related concepts.

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1. Introduction

Each process and decision in business is prone to uncertainty. Since wrong assessments and misjudgments may lead to unforeseen developments, which may have important consequences when detected (too) late, uncertainties need to be continuously

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* Corresponding author.

E-mail addresses: heckmann@fzi.de (I. Heckmann), tina.comes@uia.no (T. Comes), stefan.nickel@kit.edu (S. Nickel).

monitored and managed. Along with the increasing number of relevant uncertainties, the importance assigned to risk considerations has grown. In recent decades, we have observed this term being applied to areas such as decision theory [75,119], finance [63,64,92], actuarial science [82], health care [53,77], marketing [34,120], management [90], emergency planning [33,57,60] and psychology [2,20,38].

Particularly in supply chain management many authors have felt the need to somehow capture risk. Due to the increasing complexity and interrelation of modern supply chains, the type and nature of uncertain developments or the impact of any action have become hard or even impossible to predict [58]. Additionally, major disruptions like Hurricane Katrina, the piracy attacks off-shore Somalia, global financial crisis, floodings in Thailand, European ash-cloud, Japanese earthquake and tsunami among others revealed a lack of preparedness of supply chain managers towards uncertain developments in general [116].

A close look into the use of the term risk in general and supply chain risk in particular reveals that its meaning is far from clear. The Risk Response Network of the World Economic Forum among others have just recently identified that more time and effort has to be invested not only in conceptual or methodical work but first of all in the creation of a common definition and understanding of supply chain risk [67,117,131,135,143].

This review overcomes a hole in the literature which regards the lack of a clear definition of risk within the context of supply chain risk management. With the goal to provide a complete foundation of nowadays understanding of supply chain risk, we studied not only mathematical approaches that originate from the operations research and management science community, but also conceptual and empirical papers that provide managerial insights and risk classifications. However, the main analysis sets the focus on the mathematical body of supply chain risk literature and evaluates whether conceptual work has been transferred to mathematical approaches. Therein we reveal missing aspects of prevailing supply chain risk definitions, quantification measures and modeling approaches.

Since it is not possible to review all relevant literature, the analysis focuses on papers that either explicitly classify and define supply chain risk or that quantitatively model risk for supply chain design and planning problems. The remainder of this paper is organized as follows: the next section briefly traces the development of the term risk. By doing so, it will be easier to understand the motivation for the different definitions that are presented subsequently. We focus on the use of risk in theory and practice, particularly the integration of risk management in corporate systems, and existing risk management approaches, regulations and standards. Section 3 outlines existing concepts of supply chain risk in research and practice. In Section 4, we derive important characteristics that drive today's understanding of risk. Presented as core concepts of risk consideration, these characteristics may also be used to define supply chain risk. Section 5 provides a short discussion on measures that are used to quantify risk in the majority of analyzed papers. The following Section 6 reviews papers with regard to their modeling approach and solution techniques applied. The conclusion and an outlook outlining ideas for future research are provided in Section 7.

2. The evolution of risk

In spite (or possibly because) of its long history, the term risk is still vague and often ill-defined. Although in everyday language the term is frequently used and easily understood [97], the underlying concepts are hard to define and even harder to assess. The reason for the widespread, heterogeneous and inconsistent

definitions of risk can be traced back to its evolution, the continuous change of its nature, its meaning, and its purpose of use.

The origin of the word risk cannot be clearly determined, since this term seems to have roots in different cultures. An etymological analysis of the European notion of risk leads to the Greek navigation term *rhizikon*, describing the need to avoid “difficulties at the sea” [40]. Understood in this sense, the best approximation of the meaning of risk would be *fear* or *adventure*. The former refers to commercial activities and implies physical and mental distress, whereas the latter means pecuniary ventures as a strategy to engross the self-worth. In the 14th century, when the maritime trade between Northern Italian city states started to increase, traders adopted this perception and regarded *risk* as the danger of losing their ships. For instance a spice merchant would think of potential situations that could cause his ship to be lost: storms, piracy, mutiny of the crew, or diseases. Today, these ‘what-if-stories’ are largely used in planning and commonly referred to as *scenarios* [27]. They reveal potential developments and their consequences [73]. However, the ultimate reason for the high risk of running a spicery business did not reside solely from external events (such as storms or piracy), but also from the fact that the merchant usually owned only one ship – a single supply channel – and all his capital had been invested in the goods transported by it. Because the consequences of losing the ship were devastating for the merchant, his business was strongly *vulnerable*. The business of a merchant who owned more ships or who additionally dealt in salt trade or had a commercial partnership – diversified business risk – was less vulnerable. Such a merchant would have less reasons to be anxious. Within this context, risk expresses the fear that economic activities lead to the loss or devaluation of an important asset or a decrease in the performance of the business. Although the supply chains have become more complex, and are caught in a crossfire of a vast amount of influences, today's supply chain managers are essentially confronted with a similar situation to the merchants in the 16th century: In order to prevent their businesses from losing value, they need to identify alternatives, before or while changes to their supply chain and its environment occur. The famous and much discussed example of supply chain risk encountered by Nokia and Ericsson reveals, how the degree of preparedness leads to different outcomes [101]. Although these organizations had to deal with the same direct consequences of an unexpected incident, Ericsson suffered deeply from a supplier shortfall possibly provoking them to leave the mobile market [101,127,129], while Nokia could manage to acquire backup suppliers and alternative production capacities.

While the aforementioned understanding of risk is based on the fear of losing an investment, another view focuses on the probability of events that result in loss. At the beginning of the 17th century, *risk* became prominent in mathematics, when Blaise Pascal (1623–1662) and Pierre de Fermat (1601–1665) started to measure uncertainty in gambling [47]. Their work led to the development of *Probability Theory*, which still dominates the modern concept of risk [16]. In fact, the connection between probability theory and risk has been observed since the 1950s and has been applied to many research domains. As the performance of supply chains is becoming increasingly uncertain due to unexpected changes, authors transferred this basic probability-based risk concept to supply chain risk management. The probability of flooding, earthquakes, and tsunamis in the Asian region, for example, make supplier shortfalls more realistic and more threatening for supply chains as can be seen in a number of cases. However, less probable events like ash clouds in European air space also demand for appropriate treatment.

Contributions in supply chain risk management mainly discuss the identification of triggering-events and the assessment of their

probabilities of occurrence – although this risk perception might be limited for supply chains. The more general concept of risk associated with the fear of losing (business) value has not evolved.

3. Existing approaches of supply chain risk definitions

Although the topic is being considered as increasingly important, there are only a few authors explicitly defining supply chain risk. Those that do, found their definition on the assumption that supply chain risk is a purely event-oriented concept. This risk perception is in accordance with the risk understanding developed over the last four centuries that strongly relates risk to the

probability of occurrence of disruptive events. In the context of supply chain risk management, events are characterized by their probability of occurrence and their related consequences within the supply chain. The reasons for the occurrence of risk (i.e., the initial or so-called triggering event) are not relevant in this classification: it can be found within one firm, within its supply chain or within the supply chain's environment [71]. While some authors analyze the consequences of an event for a single focal firm [151], others focus on the performance of the supply chain as a whole [71], which can be affected by the occurrence of cascading effects that propagate through the entire network.

Among the first authors to establish a supply chain risk definition were March and Shapira: they define supply chain risk

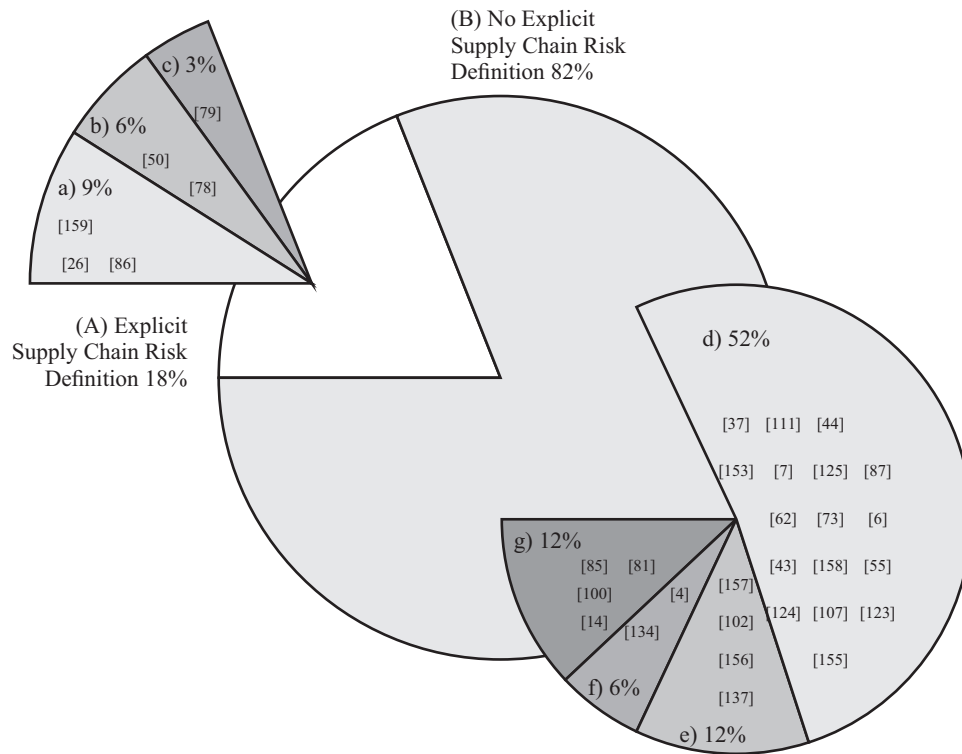


Fig. 1. Analysis of supply chain risk definitions. Articles provide (A) explicit supply chain risk definitions and define risk as a) the probability and adverse outcome, b) the supply risk by Zsidisin [162], or c) the deviation from the expected. Majority offers (B) no explicit supply chain risk definition and imply risk to be d) an event, e) a deviation from the expected/objective, f) a probability, or g) provide no further insight to the definition of risk.

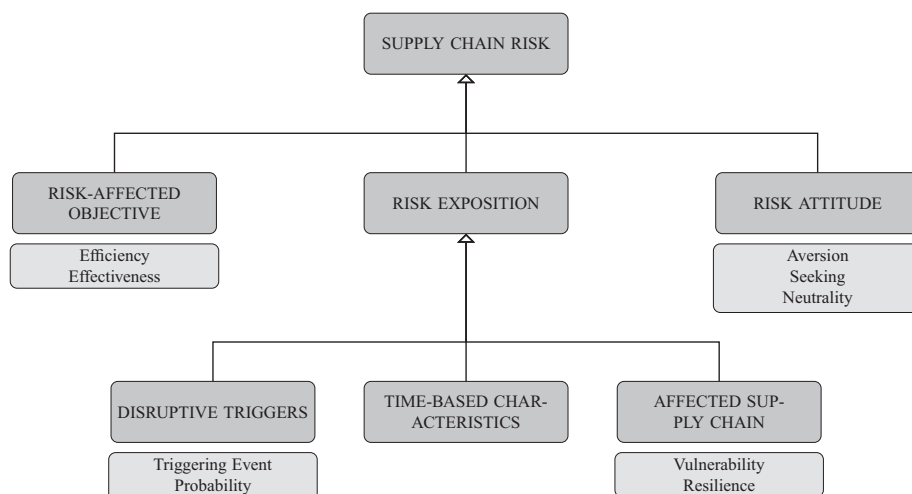


Fig. 2. Core Characteristics of Supply Chain Risk.

as the “variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values” [90]. Zsidisin provides a review of the literature and industrial practices derived from case studies in order to derive a definition of *supply risk* [162]. The author proposes a definition of supply risk that relates the occurrence of an incident with the inability of the affected companies to cope with the consequences. His definition is adopted by others as well [50,78]. Much conceptual work has been provided by Jüttner, Peck and Christopher. In a common paper the authors define supply chain risk as “the possibility and effect of mismatch between supply and demand” [67]. Likewise, Peck defines supply chain risk as “anything that [disrupts or impedes] the information, material or product flows from original suppliers to the delivery of the final product to the ultimate end-user” [105]. However, most conceptual research is dedicated to the categorizations of triggering events that are often synonymously referred to as supply chain risk, which is often understood as a starting point for risk identification [74], see discussion in Section 4.

Fig. 1 shows the result of the paper analysis with respect to the definition of supply chain risk. Note, we put the emphasis of our analysis on the evaluation of mathematical-based models, therefore, references like [67,90,105,162] are missing in the Figure. Additionally, some of those papers have been selected for the analysis, although they do not directly refer to supply chain risk, but provide valuable aspects for the quantitative modeling of risk in supply chain problems. The majority of papers analyzed, however, miss to define supply chain risk, even though their emphases are put on this topic.

Taking the above references into account, we conclude that the definitions of supply chain risk are often vague, ambiguous and defy quantification. As a result, supply chain risk is still difficult to assess, monitor, control, and hardly representable in mathematical decision models.

4. Core characteristics of supply chain risk

So far, there is no unanimous definition of supply chain risk, but there is a vast amount of literature coming from multiple domains dealing with risk. We chose the following domains to represent the most relevant streams of the use of risk, although we acknowledge that there may be further definitions in other disciplines: finance, insurance, decision theory, utility theory, emergency management and health, safety, environmental and reliability engineering. Each of the following paragraphs outlines how risk is understood according to selected domains of application and explains the underlying rationales.

Based on this analysis we identify core characteristics that drive nowadays supply-chain risk understanding: The assessment of supply chain risk is closely related to the objectives that need to be accomplished by the underlying supply chain. The degree of achievement of these objectives depends on the exposition of the underlying supply chain towards unexpected and uncertain developments. Risk exposition is further classified by potentially disrupting triggers, supply chain's ability to handle irritations, and time-based aspects that align the occurrence of the disruptive triggers to the current status of the supply chain. The significance of a potential non-achievement of objectives is assessed by the risk attitude of the decision maker. These characteristics are highlighted in Fig. 2.

4.1. Objective-driven risk

Risk considerations are very popular in financial management. The aim of this area is to efficiently plan, monitor, and control the

capital resources of a company. Financial risk management seeks to predict and to handle uncertain developments, which may lead to a degradation of company's value and forestall the achievement of corporate objectives. In finance, risk is measured as fluctuations around the expected value of financial returns. Originally, researchers considered the use of mathematical models for finding decisions which could capture this perspective of risk. In the initial models, mean-variance objective functions were considered, see for instance [39,91]. In finance, the understanding of risk comprises both gains and losses. Several characterizations of financial risk subsist, most of which distinguishing market, credit, currency or liquidity risk. These risks describe the potential for losses due to movements in market prices, debt payments, exchange rates, and interest in trading certain assets, respectively. Financial risk management models attempt to predict consequences of the aforementioned movements. In contrast to the aforementioned risks it is by far more difficult to identify, model and assess financial losses due to *operational risk*. Operational risk is defined by the Basel II Committee as “the risk of loss resulting from inadequate or failed internal processes, people and systems or from external events” [11, p.137]. In order to determine adequate capital reserves that serve as fall back positions when operations fail, organizations need to fully understand the interrelated consequences and dynamics that occur with operational risk. Operational risk better reflects the complexity, uncertainty and diversity of risk sources that are valid for supply networks. It provides, therefore, a better conceptual basis for the notion of supply chain risk than financial risk as it is understood for market, credit, currency and liquidity risk.

The discussion shows that financial risk management is concerned with risk that refers to deviations of expected monetary objectives. Similarly, supply chain management has a significant influence on business goals and therefore provides competitive advantage, when designed appropriately in regards to meet business objectives [151]. However, in supply chain management goals can be achieved in two ways: efficiently or effectively [61,96]. While effectiveness means that achieving a predefined goal can be guaranteed even if conditions are adverse, efficiency refers to minimal spending of resources to reach this goal. The primary purpose of a supply chain is to satisfy customer's demand,

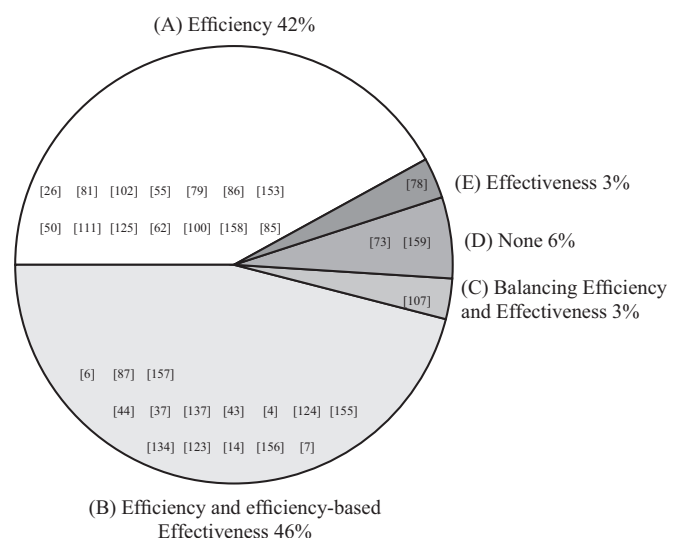


Fig. 3. Supply Chain Risk Objectives: (A) The predominantly objective is optimizing efficiency-based figures like costs, profit, or inventory. (B) When effectiveness is considered it is transferred to efficiency-based objectives by the means of penalty or shortage cost for unmet demand. (C) Efficiency and effectiveness balancing as well as (E) pure effectiveness-based approaches are limited. (D) Some work may serve for different risk-objectives.

the availability of resources and the functionality of supply chain processes, therefore, need to be guaranteed. The effectiveness in the context of supply chain management includes these aspects [19]. In contrast, purely efficiently designed supply chains provide the possibility of higher competitive advantages. Supply chain efficiency refers to a cost- and waste-minimal execution of supply chain activities [19]. The recent series of reported supply chain failures has shown that when efficiency is the sole objective, there is little buffer to enable continuity or recovery in the event of a disruption. It seems that the pursuit of efficiency and effectiveness are conflicting [78] and need to be carefully balanced.

Stock and Boyer developed a consensual definition of supply chain management that incorporates the aforementioned thoughts [138]. According to the authors the management of supply chains seeks to plan, monitor, and control a network of interdependent organizations that facilitates different types of flows between the original producer to the final customer with the objectives to maximize profitability through efficiencies as well as to achieve customer satisfaction [138]. Consequently, a definition of supply chain risk should reflect the potential non-achievement of corporate goals due to ineffective or inefficient supply chain processes. Meanwhile, most approaches concentrate on reducing monetary or financial consequences of uncertain and unexpected developments. Only a few authors consider effectiveness-based aspects like service level. Kull and Closs for instance use discrete-event simulation with the objective of increasing customer satisfaction [78]. Zsidisin defines *supply risk* and relates the occurrence of an event to the inability of the supply chain to satisfy customer's demand [162]. Fewer authors combine both concepts in order to truly balance supply chain efficiency with supply chain effectiveness. Peng et al. develop a system dynamics model for balancing inventory level and service level [107]. The majority of approaches, however, focus on a purely efficiency-based representation: when effectiveness is considered, it is measured in terms of the sighted efficiency figure (costs or profit). Fig. 3 presents main results of this analysis with regard to the mathematical approaches considered.

4.2. Risk exposition

Besides the objectives set to the supply chain, the exposition towards unexpected or uncertain developments have meaningful influence on how supply chain risk is understood. The risk exposition is specified by the occurrence of a so called-triggering event, as well as by characteristics of the underlying supply chain. While the former is further specified by the probability of occurrence and the effect within the supply chain, the latter is described by concepts like vulnerability or resilience. Additionally, time-aspects need to be considered when referring to disruptive triggers and the preparedness of the affected supply chain.

4.2.1. Disruptive triggers

A disruptive trigger is further specified through the concepts of probability and event.

Probability. The central aspect of risk perception in most research areas is the availability of probability distributions. Decision theory, for instance, aims to support decision-makers in the construction or identification of an optimal or at least a satisfying decision. This is difficult in complex situations, when the assessment and evaluation of the consequence of decision is affected by different types of uncertainty [32,46]. The effective and efficient practice of supply chain management in today's globalized world depends on the collaboration between geographically dispersed organizations [76]: (local) information must be collected, evaluated and shared across organizational boundaries [48].

Rosenhead et al. were the first to classify a decision process according to the available information into three categories: certainty, risk and uncertainty [119]. Under *certainty* all parameters are deterministic and known. The relation between information (input) and the decision (output) is unambiguous. Situations that are not certain comprehend some kind of fortuity. Reasons for the need to make decisions under these circumstances vary from lacking time and resources to collect, process and evaluate information to the inherent complexity of systems that forestalls predicting the consequences of a decision [32,59,84,161]. To distinguish between these fundamentally different situations, two categories are introduced: decision making under *risk* relies on probability distributions, which govern the relation between input and output. Decision making under *uncertainty* needs to be made despite the lack of information about the likelihood of parameter changes.

Most authors adopted this categorization and refer supply chain risk to the extent of information availability about randomly changing supply chain parameters – assuming probability specifications are at hand. Yet information processing needs to respect the fact that the situation, its development and the information about both may be uncertain, fast-changing and with varying degrees of relevance and reliability. Still supply chain managers need to make decisions even when no information about the type of fortuity is available. Supply chain risk therefore addresses both decision making under risk and under uncertainty.

The type of fortuity used to describe the development of uncertain parameters is depicted by uncertainty models. The literature analysis follows the categorization of Owen and Daskin [103]. The authors distinguish between probabilistic approaches and scenario planning approaches. While the former explicitly consider probability distributions, the latter evaluate generated sets of possible future values, which can be weighted by discrete probability values, but do not have to [103]. Table 1 shows the results of this analysis.

Triggering Event. The strong relation between the concepts of probability and risk is adopted by health, safety, environmental (HS&E) as well as by reliability engineering. However, a new aspect is emphasized by the implication that risk is understood as an event or a series of events. The international engineering standard ISO14971 defines and measures a risk R as the product of probability and harm of an event e : $R = P_e S_e$, where S_e and P_e refer to the severity and probability of e respectively [1]. Most of today's supply chain risk definitions start from the assumption that events are the decisive factor determining risk [154]. Consequently, huge efforts are invested in gathering, analyzing and assessing information to control potential triggering events that could materialize supply chain risk. To assess supply chain risk, triggering events are modeled as a function of their severity in terms of impact on the supply chain goals and their frequency of occurrence. Different terms are often used synonymously to refer to triggering events, e.g. *disturbance* [141], *disruption* [128], *disaster* [139], *hazard* or *crisis*. According to Svensson a disturbance is a “random quantitative or qualitative deviation from what is normal or expected” [141]. A negative consequence of disturbance is related to “a deteriorated goal accomplishment in terms of economic costs, quantitative deviations [...] and qualitative deviations”. Wagner and Bode state that a disruption is characterized by its probability, severity and effects [151]. A disruption is further described as a combination of the triggering event, which is characterized through frequency of occurrence and magnitude, and a consequential situation, which threatens the normal course of business operations. A disruption is regarded as more severe and often persist for a longer period in time than a disturbance.

Klibi and Martel combine the availability of probability information and the extent of impact related to each triggering event.

Table 1
Uncertainty model of uncertain parameter development.

Uncertainty model	Reference	Share (%)
Probabilistic approach	[7,37,43,155,159]	22
Scenario approach	[4,6,7,14,50,55,62,79,87,102,111,123–125,134,137,156,157]	78

The authors distinguish between random, hazardous, and uncertain events. The former are described by probability distributions and occur within single periods. Hazardous events affect supply chain's performance in adjacent periods. They are considered to be rare but repetitive. No probability information is available for uncertain events, however, they are considered to have enormous impact on the supply chain in adjacent periods [73].

As supply chain risk is understood as a triggering event, most authors focus on categorizing supply chain risk with regards to the triggering events in order to distinguish it from other business risks [151]. This serves to better understand and manage its inherent diversity. While the majority of the approaches relate supply chain risk to the source or root causing the deviations, some authors relate risk to ultimate consequences. According to Jüttner et al. and Kajüter these approaches distinguish between cause- and effect-oriented definitions of supply chain risk [67,70]. Major efforts in the Anglo-American supply chain risk management literature have been dedicated to cause-oriented methods. The rationale behind is that by knowing the cause, appropriate measures to reduce the likelihood of occurrence can be implemented. Additionally, the taxonomies differentiate between sources related to the supply network and to supply chain processes. Table 2 shows a summary of relevant supply chain risk categories and subcategories as defined in literature.

In the following the focus is set to the analysis of *risk sources*. Depending on whether the risk source lies within or beyond the supply chain boundaries, we find endogenous and exogenous origins for the supply chain risk. As a supply chain usually consists of several different interconnected companies, Götze and Mikus further distinguish endogenous risk sources as “beyond company borders” and “corporate-wide” sources [52]. Another classification refers to the possibility of controlling the risk: Jüttner et al., Waters, and Wagner and Bode distinguish internal from external risk sources that are beyond the managers' control (e.g., policy or market risk) [67,151,154]. Christopher and Lee, Jüttner et al., and Christopher and Peck find three different types of *network related sources of supply chain risk*: lack of ownership, chaos, and inertia [29,30,67]. Lack of ownership refers to the increasing number of logistic partners and the resulting unclear lines of responsibilities. The increased complexity of the supply network, significant changes in the environmental conditions, and market signals, drive inadequate mitigation [67], which result from over-reactions or distorted information. Among others, *process-related sources of supply chain risk* are for example referred to the Supply Chain Operations Reference (SCOR) model. Risk sources are assigned to the key processes defined within the SCOR model: plan, source, make, deliver, and return. Consequences of “SCOR-process-risks” [160] are further characterized by quality, delay, breakdown, costs etc., to facilitate analysis and communication.

An alternative approach categorizes supply chain risk according to the *area* that is affected by the occurrence of risk. Perspectives of this category refer to the basis of the extent, the controllability, or the network-wide location of the impact. Kajüter differentiates between cumulative, additive, and singular supply chain risks [69]. Cumulative supply chain risks intensify as they propagate along the supply chain processes. Additive supply chain risks have negative effects along the supply chain if they co-occur. Finally, singular supply chain risks are locally isolated, thus not affecting

any other parts of the supply chain. Tang provides a set of dimensions referring to the *extent* of impact by addressing the risk level of certain events and differentiating between operational and disruption risks [144]. Simchi-Levi focus on the role of decision-makers and provide two dimensions of analysis by distinguishing known-unknown/ unknown-unknown and controllable/uncontrollable risk [129,130]. The first dimension refers to the predictability of unknown events. The latter describes the ability to manage and limit frequency and impact of risk. The unknown-unknowns are risks that can hardly be predicted. Terrorist attacks, epidemics, or geo-political instability are typical examples, but due to the climate change, also extreme weather events and related natural catastrophes will become harder to predict. The known-unknowns are risks that can be predicted from analyses of past events, for example by the means of statistical data analysis, e.g. meantime to failure, supplier lead time [130]. Controllability refers to the ability to manage and limit frequency and impact of risk. This classification is subject to individual expert assessment: the predictability and controllability of execution problems strongly depend on the nature of the business environment and the sighted level of business objectives. Moreover, the binary character makes it hard to compare the degree of control or knowledge between different events.

Based on these categorizations, Fig. 4 shows those approaches that strongly differ between the source of uncertainty and the affected area. For instance Goh et al. develop a stochastic model for a facility location and distribution planning problem under supply, demand, and exchange rate risk, where uncertainty arises from supply, demand and exchange rate, respectively [50]. Supply chain risk is regarded as the source of uncertainty. Similarly, Mak and Shen as well as Sawik regard risk as the disruption risk, while the source of uncertainty is modeled as a distribution function of the disruption [87,124].

Other sources of uncertainty are referred to as supply risk [37,43,44,78,79,86,123,125,159], demand risk [6,14,37,50,79,111,125,134], or risk of (total) cost [6,50,155]. Most approaches, however, describe supply chain risk as the deviation of the affected objective, which is most often profit-, cost-, or cash-flow-oriented and therefore referred to as *monetary figure* [4,7,26,55,62,81,85,100,102,125,137,156–158]. Minor work is dedicated to regard risk as customer's satisfaction [78] or supplier failures [153].

4.2.2. Affected supply chain

From emergency management another dimension of risk exposition can be identified. To prevent harm from human lives, to keep safety and to ensure sustainable growth, authorities and policy makers have sought to anticipate and prepare for the unexpected [108,148]. Examples include emergency management plans [5] or the design of stress tests for critical infrastructures [113]. In these contexts, risk is often determined as a function of hazard, vulnerability and exposure [22,95]. This distinction is targeted at supporting decision-makers by distinguishing the external components of risk that can hardly be influenced (such as a natural hazard) from the internal values that can be controlled or manipulated [17]. This approach does not only regard risk as a threat deriving from triggering events, but also as a concept that depends on characteristics of the underlying organization. Only

Table 2
Supply chain risk categories.

Category	Subcategory	Perspective	Type of supply chain risk (characteristic of supply chain risk source)	Author
Risk sources	Network	Location	Supply chain exogenous; Beyond company borders supply chain endogenous;	[52]
			Corporate-wide supply chain endogenous	[68]
		Controllability	Supply; Demand; Environmental	[24]
			Supply chain network (physical network, financial network, informational, relational, innovational network)	[67]
			Internal	[154]
			External	[151]
			Internal (demand side, supply side, regulatory/legal/bureaucratic, infrastructure, catastrophic); External (regulatory/legal/bureaucratic, infrastructure, catastrophic)	
			Lack of ownership	[29]
			Chaos	[67]
			Inertia	[30]
			Quantitative; Qualitative	[140]
			Supplier-related (disruptions, delays, systems, information processing, intellectual property, procurement, receivables); Internal (disruptions, delays, systems, information processing, procurement); Customer-related (disruptions, delays, systems, information processing, receivables)	[28]
		Assessment Stakeholder	Plan (quality, delay, breakdown, costs); Source (quality, delay, breakdown, costs); Make (quality, delay, breakdown, costs); Deliver (quality, delay, breakdown, costs); Return (quality, delay, breakdown, costs)	[160]
			Environmental; Supply; (Intra-corporate) process; (Intra-corporate) control; Demand	[72]
			Research & development; Supply; Production; Distribution; Financial; Personal; Management	[80]
			Order processing; Inventory; Warehouse; Packing; Transport	[52]
Target area of risk	Process	SCOR levels		
		Controllability		
		Organizational functions		
		Logistical operations		
		Propagation		
Target area of risk	Location	Extent of impact	Corporate; Supply chain wide	[52]
		Controllability	Operational (demand, supply and cost deviations); Disruption (natural and man-made disasters)	[144]
		Known-unknown/unknown-unknown; Controllable/uncontrollable		[130]
		Cumulative; Additive; Singular		[69]

some authors have recently highlighted the correlation between magnitude of supply chain risk and the capability of resistance of the underlying system [73,86].

The concept used to describe the extent to which a supply chain is susceptible to a specific or unspecific risk event is called *supply chain vulnerability*. It is remarkable that prevalent definitions of both triggering event and supply chain vulnerability use concepts and computational formulae that are similar, often even identical, to supply chain risk definitions. A concept closely related to supply chain vulnerability is *supply chain resilience* describing the ability of a supply chain to overcome vulnerability. In general, vulnerability is defined as a concept that describes “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” [147]. In this sense, supply chain vulnerability can be understood as a concept that comprehends the supply chain as a system within its socio-economic environment comprising the abilities to respond to the hazard and cope with the damage that could occur. Three main perspectives of definitions describing the concept of supply chain vulnerability can be distinguished within the contemporary literature: definitions are either identical to the definition of supply chain risk, or they relate to the extent of supply chain exposure or they refer to characteristics of the underlying supply chain. Table 3 illustrates the prevailing perspectives on vulnerability.

The first perspective in Table 3 refers to the definition of supply chain risk: authors from the fields of supply chain management, transportation systems and network analysis understand vulnerability as a combination of the likelihood of a triggering event and its related consequence [36,65,128,140–142]. Defining supply chain vulnerability as “something [that] is at risk” [105, p. 132] requires an understanding of what is meant by supply chain risk. Additionally, there is no clear and unanimous distinction between the definition and understanding of supply chain vulnerability and supply chain risk.

Further work focuses on developing a conceptual and rather qualitative understanding of supply chain vulnerability by relating it for instance to *propensity*, *susceptibility* and *exposure* [8,25,30,67,150,152]. A first step towards a systematic understanding of supply chain vulnerability was taken by Wagner and Bode [150]. Following their argumentation certain structural supply chain characteristics can influence corporate loss given a supply chain disruption. Similarly, Barroso et al. define supply chain vulnerability as the “incapacity of the supply chain to react to the disturbances at a given moment, and consequently to reach supply chain objectives” [10].

The concept of *resilience* is applied in many different disciplines such as ecology, engineering, sociology, psychology, economics and organizational analysis. The overall understanding of resilience relates to the ability of the underlying system (material, network, individual, companies or corporate entities) to adjust or maintain essential functions under stressful and harsh conditions. In engineering resilience refers to a material's characteristic “to recover its size and shape after the deformation caused by especially compressive stress” [94]. Particularly in crisis and emergency management, resilience is often defined as the response to an actual threat, the ability to “bounce back” to the initial state [18,33,42,89]. This state is considered as a point of reference, although its optimality is not guaranteed. In fact, in many situations it can be advantageous to adjust to or strive to attain a new state. In supply chain management, reasons may be that environment and operating conditions have changed in a way that turn the initial state unfavorable, or because the supply chain has learned from the disruption and adapts to the new (desired) state to improve preparedness. The first definitions of resilience referring to supply chain management were developed in 2004 at the Cranfield University [30] and in parallel studies at the MIT [128]. This work resulted in a first concise definition of supply chain resilience, which is still dominating: supply chain resilience is defined as a supply chain's ability to return to its original or

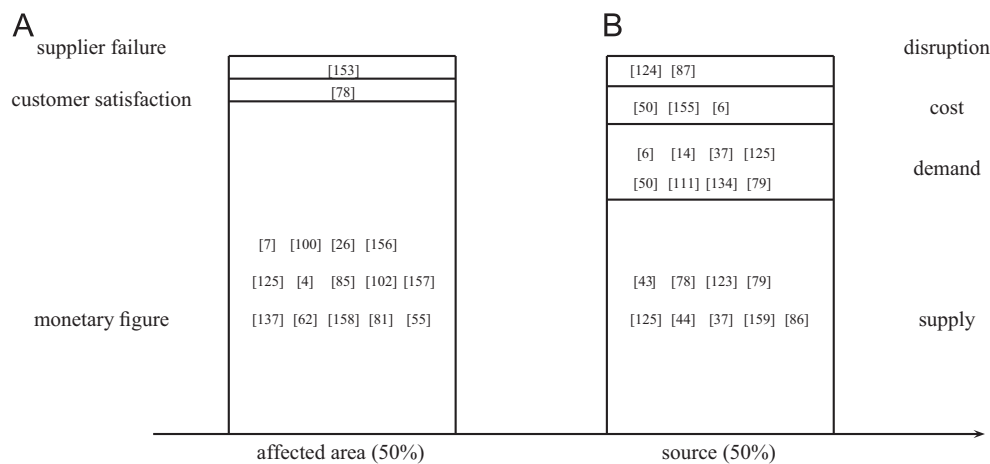


Fig. 4. Literature analysis of supply chain risk categories: (A) Supply chain risk is classified upon the affected KPI and/or (B) supply chain risk is understood as the source of uncertainty and therefore related to the uncertain parameters.

Table 3
Supply chain vulnerability definitions.

Perspective	Definition of supply chain vulnerability	Author
Supply chain risk	Supply chain vulnerability = $S_e P_e$ "something is at risk; vulnerable: likely to be lost or damaged" vulnerability as a construct consisting of two components, namely "disturbance" and "the negative consequence of disturbance"	[36,65,128] [105] [140–142]
Supply chain exposure	"propensity of risk sources and risk drivers to outweigh risk mitigating strategies" "an exposure to serious disturbances, arising from risks within the supply-chain as well as risks external to the supply-chain"	[67] [25,30]
Supply chain characteristics	a susceptibility to incidents that can reduce availability of network resources "is a function of certain supply chain characteristics" "incapacity of the supply chain to react to the disturbances at a given moment" "characteristics and circumstances of a system [...] that make it susceptible"	[8,15] [150] [10] [17,109,147]

move to a new, more desirable state after being disturbed [30,49,105,110]. While this understanding is uncontested in the supply chain management literature, different attitudes prevail about how supply chain resilience is related to supply chain vulnerability and to supply chain risk and how supply chain resilience can be achieved. Consequently, definitions on supply chain resilience either refer to the ability to overcome supply chain vulnerability [10,109,140–142] or to the ability to reduce supply chain risk [42,66,104]. A research analysis of current literature reveals dimensions, which are deemed to be important to increase supply chain resilience. According to Rice and Caniato the most relevant "resilience capabilities" are *flexibility* and *redundancy* [114]. Both can be further specified through flexibility-related concepts like agility [30], responsiveness [23], velocity [66], or intra-corporate concepts such as supply chain risk management culture [30], collaboration [115] and visibility [30].

Some conceptually oriented work has already described the need to combine the event-driven perception of supply chain risk with a systematic-driven view on the underlying supply chain [66,150]. Other quantitative works pointed out the importance of combining disruptive triggers with the configuration of the supply chain [73,78,86,126], but only a few applied this perception within their models, see for example [6].

4.2.3. Time-based characteristics

A universal aspect of risk, which is applied in many different domains, is the consideration of time. In financial management, for example, the time horizon length has a meaningful influence on

the assessment of risk and has attracted much attention [21,51]. In emergency or disaster management early warning systems yield to increase the preparedness of a system with regard to reaction-time [112].

The literature on supply chain risk management has not yet considered in depth time-aspects, yet some authors point out their importance with respect to the modeling of supply chain risk [55,86,88,127,151]. As can be derived from the literature analysis, time-aspects are introduced for the modeling of disruptive triggers or for characterizing the affected supply chain. The magnitude of consequences, for instance, depends on the current work load of the affected supply chain (netting between demand quantity and available capacities). Considering the European ash cloud in 2010, it is quite obvious that the consequences would have been less severe if the Icelandic volcano had erupted during Christmas holidays, when many production facilities are closed anyway. The time of an impact is important in the consideration of supply chain risk [14]. Time-based characteristics that describe the ability of the affected supply chain to discover and respond to disruptive triggers are captured by Ben-Tal et al. as well as Sodhi and Tang [14,136]. The authors distinguish between time to design a solution in response to the disruption [14], time to deploy the solution, and the time of recovery [136]. Besides characterizing the affected supply chain, time-based aspects describe properties of a disruptive trigger. For example the speed of an event captures how fast parameters change during or after the occurrence of an event [88]. The time for detection of an event formalizes the time until information about the event are available [88,136]. The frequency captures the time between two triggering events [88]. The

frequency of such events has increased considerably over the last years [31]. The duration of changes evoked by triggering events is declared as a relevant temporal aspect [127,151,158].

However, the classifications of time-based characteristics are of conceptual nature and have not yet been fully transferred to mathematical approaches. The description of time-based characteristics mainly relates to supply chain modifications that were evoked by triggering events, and do not relate to decisions, risk management, and required counter measures. Changes may also arise by uneventful trends or slightly varying level shifts. As the literature analysis reveals, approaches have not paid much attention to time-based characteristics of supply chain risk so far. Although mid-term problems like inventory, supply or demand planning imply the consideration of several periods, they do not employ time for capturing risk.

4.3. Risk attitude

Derived from utility theory and applied in the field of financial risk management, risk is specified by the risk attitude of the decision maker. The subjective perception of the importance of risk is divided into three groups: risk-averse, risk-seeking, and risk-neutral. These attitudes may drive managers' decision-making processes and lead to different solutions. Supply chain risk, as risk in general, may be regarded as a subjective concept that relies on the individual's assessment of potential outcomes, rather than an objective concepts [41]. Risk attitudes and individual or organizational preferences, therefore, have a decisive influence on the measurement of future supply chain performance and consequently co-determine supply chain decisions. While most of the approaches do not explicitly consider different risk attitudes, some authors refer to subjective perceptions of the decision maker. Liu and Nagurney, for instance, suggest that supply chain managers should first evaluate the risk tolerance level of the firm before making decisions that need to last for the long-run [85]. Wakolbinger and Cruz apply a weighting factor representing an adjustable risk attitude of the decision maker [153]. Table 4 summarizes which of the analyzed approaches considered risk attitudes explicitly within their models.

Interestingly, risk-seeking attitudes are not considered in supply chain risk literature so far. A reason might be that supply chain risk is mainly related to negative developments of supply chain objectives. However, to the best of our knowledge, definitions of different attitudes towards supply chain risk do not exist in the contemporary literature. As deduced in Section 4.1, the extent of supply chain risk strongly depends on pursued goals of the underlying supply chain. Supply chain goals are detailed by the type of objective, which can be both efficiency- or effectiveness-based, and their corresponding target-values. Based on the findings so far, we provide a definition of supply chain risk attitudes as follows. The decision maker's degree of acceptance with respect to the deterioration of target-values defines his attitude towards supply chain risk. Risk-averse supply chain managers only accept a minor deterioration of target values of an efficiency- (or effectiveness-) based supply chain goal in exchange for the adherence or increase of an effectiveness- (or efficiency) based supply chain goal. Risk-seeking decision makers, however, accept higher degrees of value deterioration of a specific goal in exchange for the adherence or increase of an opposite one. Risk-neutral supply chain managers prefer neither of the two objective types. If target values of efficient- and effective-based supply chain goals are too tight, these objectives can be mutually exclusive. For example, a targeted service level of 100% in addition with a sighted level of zero logistic cost might be impossible.

Table 4
Risk attitudes considering approaches.

Ref	Single risk attitude			Multiple risk attitudes adjustable
	Risk-averse	Risk-neutral	Risk-seeking	
[6]		✓		
[7]	✓	✓		
[26]	✓			
[55]		✓		
[73]	✓	✓		
[81]	✓			
[85]	✓	✓		
[87]		✓		
[100]				✓
[102]	✓			
[124]	✓	✓		
[123]		✓		
[125]	✓	✓		
[137]	✓			
[153]				✓
[155]				✓
[157]	✓	✓		

5. Risk measures

In order to assess and compare different solutions that aim to limit the extent of risk, decision-makers need to (somehow) quantify risk. Standard deviation, mean-variance approaches, value-at-risk, conditional-value-at-risk or premiums are risk measures that aim at describing the interaction of uncertainty and the extent of its related harm or benefit. Owing to the lack of quantitative measures that capture the more complex realities of supply chains, these measures – developed in finance and insurance contexts – are applied for supply chain risk, too. Starting from these concepts, supply chain risk is also measured by the likelihood and the severity of adverse effects or the extent of loss [45,56,97].

In the following, several commonly used supply chain risk measures are introduced and briefly discussed.

Variance or standard deviation are widely used as a measure of supply chain risk, although several authors have been arguing that they are problematic as measures of risk in general [13,35,106]. Both concepts evaluate the wideness of a distribution and consider not only negative but also positive deviations from expected returns [121]. Consequently, a surplus of the expected is considered as risky as a equal-sized loss. According to Cox the most common critique in the theoretical decision analysis and financial economics literatures are the restrictions under which the mean-variance analysis is applicable [35], e.g. risk factors have normal or location-scale distributions and utility functions are quadratic, implying that less money is preferred to more, for some amounts [9,91]. The difficulties of using probabilities in the light of growing complexity and uncertainty have already been discussed above. Deviation-based measures, like variance, standard deviation, expected or absolute values of deviation are applied by [4,6,7,55, 62,79,87,102,123,134,153,156,157].

In financial engineering and financial risk management positive and negative deviations are referred to as *upside-* and *downside-risk*, respectively. In that sense downside-risks reflects the risk associated with undesirables outcomes, i.e. losses. Value-at-risk (VaR) and conditional-value-at-risk (CVaR) are used in portfolio theory as percentile measures of downside risks. Both concepts describe different parts of a profit or loss distribution and their use is governed by the objective of the decision maker as well as by the availability and quality of distribution estimates [121]. VaR is defined as a threshold value associated with a specified confidence

level of outcomes. Let X be a random variable most often describing a loss and $F(X) = \text{Prob}\{X \leq z\}$ the cumulative distribution function of X . The VaR_α of X with confidence level $\alpha \in [0, 1)$ is

$$\text{VaR}_\alpha(X) = \min\{z | F_X(z) \geq \alpha\}$$

By definition VaR is a lower α -percentile of X and therefore does not account for the distribution properties beyond the confidence interval. The indifference of VaR to extreme parts of the distribution can be both a desirable or undesirable property. When stable distribution estimates are not available VaR is predominantly used. However, extreme outcomes impose a particular threat and need to be explained especially if VaR is exceeded. $\text{CVaR}_\alpha(X)$ equals the conditional expectation of X subject to $X \geq \text{VaR}_\alpha(X)$. In other words it describes the average loss beyond the specified confidence level. Developed by Rockafellar and Uryasev CVaR attracts much attention due to its mathematical properties that are especially suitable for optimization problems [118,121]. Acerbi and Tasche defined an equivalent of CVaR named *expected shortfall* [3]. Sarykalin et al. provide a comparative discussion of both concepts as well as suggestions of when to use which concept [121]. For further insights we refer to their work. The application of downside risk measures within the context of supply chain problems is very common as can be deduced from the literature analysis. [86,111,123,125] apply VaR , [111,123–125,137] apply CVaR and [26,55,157] use other downside risk measures.

In actuarial science risk is described by a non-negative random variable, that models a claim size caused by a policy. Actuaries develop models to quantify and price risks, i.e. they require probability distributions of the risk regarded as well as preference function to these probability distributions [82]. The price charged by the insurer for taking the risk is called a *premium*. The decision to transfer supply chain risk to an insurance has to be investigated carefully, as it does not necessarily cover the loss of the insured.

Other authors define approach-specific concepts like the number of hits [73] or use old-established measures like the mean-variance related to the profit [85]. Nagurny et al. define risk functions for each supply chain partner that depends on the flow related to each partner and on the total flow within the network. These functions are used as an input for the model. Several authors apply probability as a measure of risk [4,37,43,44,78]. Azaron et al. for instance measure the risk associated with a supply chain design problem by the probability of not meeting a certain cost level or budget [4]. Cui et al. express supply chain risk as the probability that a certain facility serves a certain customer at a certain level [37]. Some authors do not quantify the degree of risk related to a solution, which is most-often the case, when supply chain risk is understood as the uncertainty of input parameters [14,50,81,155,158]. This group is referred to as not further quantified (NFQ).

Fig. 5 summarizes the analysis on risk measures applied in the literature under investigation.

Most approaches concentrate on reducing monetary consequences of uncertain and unexpected developments, see Section 4.1. Meanwhile they predominantly evaluate the impact of changes of monetary policies (prices) or fiscal policies (taxation) with measures developed for the quantification of financial risk. However, financial risk is taken care of in financial risk management and supply chain risk management should be responsible for monetary losses within supply chain management. Additionally, we emphasize that objectives of supply chain management have different dimensions. Effectiveness-driven goals like customer satisfaction or supplier reliability ask for different measures like efficiency-based objectives.

6. Risk-aware supply chain optimization

As supply chain risk management is a discipline that attracts the attention of researchers from different domains, the existing

literature provides various methodological approaches. In addition, the previous discussion has shown that supply chain risk consists of several relevant aspects. There are literature reviews that analyze the existing work on some of these core characteristics: Snyder et al. review papers from the operations research community that relate solely to supply chain disruption, hence that focus on *disruptive triggers* [133]. Reviews focusing on the *affected supply chain* discuss the design and planning of mitigation alternatives [54,146]. Affiliated work includes topics like critical infrastructure and network reliability [99,132].

Others classify and discuss general supply chain risk management approaches more broadly [131,135,143,149] and derive managerial insights [127,131,144,145].

Tang classified various quantitative and qualitative approaches upon the supply chain management unit that is considered to deal with risk (supply, demand, product, or information management) [144]. Within each category the author further analyzes and differentiates available approaches upon the parameter considered as uncertain (demand, lead times, costs, yields), problem type (supply network design, supplier relationship, supplier selection process, supplier order allocation, supply contract), management strategy (postponement, process sequencing), or industry, respectively. Singhal et al. provide a review that classifies literature by research approaches and key issues of supply chain risk management [131]. They divide analytical risk modeling approaches into modeling type (mathematical, simulation, and multi-agent) and modeling settings (linear, integer, dynamic, and stochastic problem settings). According to Singhal et al. the latter refers to the nature of the study and scope/domain of the research problem.

The aforementioned surveys give a valuable overview of the supply chain risk management literature reaching across domains and methodologies. This section provides additional information and insights with the focus set to mathematical approaches that model supply chain design and planning problems and that explicitly refer to the consideration of supply chain risk. As we should be interested in how supply chain risk is defined, quantified, and modeled today, we omit the aforementioned related work. We analyze the modeling paradigms and techniques that solve the problems.

6.1. Modeling approaches

In order to describe mathematical formulations for optimizing supply chain risk problems, this paragraph focuses on universal

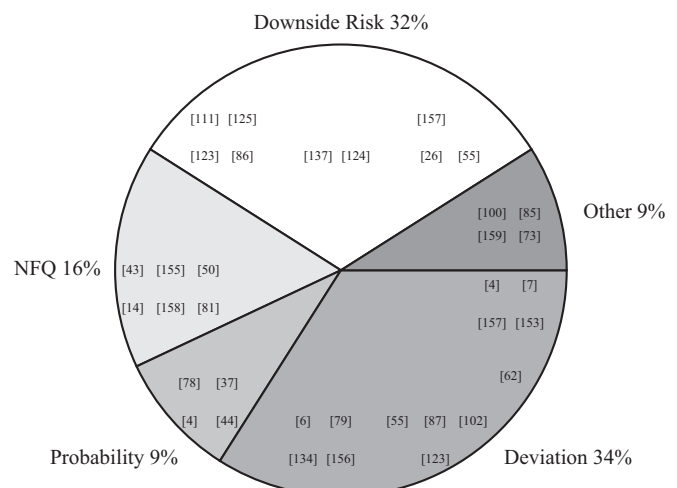


Fig. 5. Measures applied for quantifying supply chain risk: Downside risk measures like VaR and CVaR and measures of (absolute, expected, and standard) deviation are among the most applied measures.

Table 5
Categorization of modeling approaches.

Linearity	linear programming	LP
	Non-linear programming	NLP
	Mixed integer/integer linear programming	MLP
	Mixed integer/integer non-linear programming	MNLP
Objective function dimensionality	Single-objective function	SOF
	Multi-objective function	MOF
Risk statement placement	Within objective function	OF
	Within constraints	CON
	Within constraints and objective function	OF/CON

categories as well as on aspects tailored for supply chain risk considerations.

Classical categories have been proposed by Beamon among others [12]. He distinguishes between deterministic analytical, stochastic analytical, economic, and simulation models. Sahebi et al. just recently provided a classification based on Beamon's and Mula et al.'s approaches [12,98]. Sahebi et al.'s approach tackles relevant modeling aspects like the linearity of model formulation, dimensionality of the objective function, analytical model and purpose [122]. This classification is more suitable for the analysis of existing literature. Since the purpose of the mathematical formulation has been analyzed in Section 4.1, this aspect is skipped in the following presentation.

The risk statement is a further relevant aspect of description. Supply chain risk should be either minimized by the objective function, restricted by specific constraints or be balanced by its consideration in both statements. Often risk measures are introduced in the objective function and other risk related parameters are used in constraints.

Considering these aspects, we used the following criteria to classify the models:

- Linear programming, non-linear programming, mixed integer/integer linear programming, mixed integer/integer non-linear programming;
- Single and multi-objective functions; and
- Risk considerations within the objective function, within the constraints, or within both.

Table 5 summarizes the various aspects of modeling approaches that classify the reviewed papers.

Table 6 shows the result of this analysis. The majority of the reviewed papers applies linear programming and more precisely mixed integer programming approaches. Especially location-allocation type of problems favors the mixed integer approach [4,6,37,50,62,87,111,137]. The linear programming approaches considered tactical problems, like production, logistic or supply chain planning [14,43,134,156,157] as well as strategic decision models like supplier selection/portfolio or supply chain design problems [4,6,37,50,62,87,111,125,137,155,159]. Very rarely non-linear approaches are chosen [4,7]. Models exclusively considering multi-objective functions are of minor interest [4,62,159], although the need to balance different types of supply chain objectives would motivate multi-objective approaches. Therefore, the consideration of supply chain risk is stated mainly in both objective function and constraints.

6.2. Solution techniques

This section follows the classification of solution methods provided by Melo et al. [93]. They defined four categories that determine different solution techniques. The first category *General solver*, *exact solution* refers to a problem's solution obtained by mathematical

Table 6
Modeling approaches of the reviewed papers.

Ref	Linear		Nonlinear		Objective		Risk statement		
	LP	MLP	NLP	MNLP	SOF	MOF	OF	CON	OF/CON
[4]				✓		✓	✓		
[6]		✓			✓				✓
[7]				✓	✓				✓
[14]	✓				✓			✓	
[37]		✓			✓			✓	
[43]	✓				✓		✓		
[50]		✓			✓				✓
[55]		✓			✓		✓		
[62]		✓				✓	✓		
[79]		✓			✓		✓		
[87]	✓				✓				✓
[102]		✓			✓				✓
[111]		✓			✓				✓
[123]		✓			✓	✓			✓
[124]		✓			✓	✓			✓
[125]		✓			✓	✓			✓
[134]	✓				✓				✓
[137]		✓			✓				✓
[155]	✓				✓	✓			✓
[156]	✓				✓				✓
[157]	✓				✓	✓			✓
[159]	✓					✓			✓

programming software. The solution is either optimal or good enough with respect to a pre-determined acceptable gap specified by the decision maker. By introducing computational time restriction an off-the-shelf solver provides solutions of the second category, namely *heuristic solution*. Specific solution algorithms offer exact or heuristic solutions. The former are obtained by special-purpose techniques such as decomposition methods, column generation, branch-and-cut, and branch-and-bound. The latter are determined by heuristic-based approaches (Lagrangian relaxation, linear programming based heuristics and meta-heuristics) when problem sizes are huge. Table 7 summarizes the analysis of solution techniques.

7. Conclusion

An increase in observed supply chain disruptions has raised awareness for supply chain risk management in recent years. Unfortunately, the understanding of what exactly is meant by supply chain risk, which information should be monitored, and how risk management and mitigation can be designed in the light of these risks is heterogeneous. As risk considerations are already deeply embedded in other fields and partly applied in supply chain management, we conducted an extensive literature analysis on risk concepts in general and on conceptual as well as mathematical supply chain risk approaches in particular. Based on the literature review we identified core characteristics that are used to define, quantify and

Table 7
Solution techniques of the reviewed papers.

Solution technique	References	Share (%)
General solver, exact solution	[6,7,14,55,111,123–125,134,137,156]	46
General solver, heuristic solution	[14,102,157]	13
Specific algorithm, exact solution	[4,37,44,50,62,87]	25
Specific algorithm, heuristic solution	[37,43,79,159]	16

model risk. Adjusted to supply chain risk management these core characteristics can also define *supply chain risk*.

The identification and discussion of core characteristics allows for a re-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*.

However, the real challenge in the field of supply chain risk management is still the quantification and modeling of supply chain risk. To this date, supply chain risk management suffers from the lack of a clear and adequate quantitative measure for supply chain risk that respects the characteristics of modern supply chains. Measures predominantly used in finance and insurance are most often used in mathematical approaches for supply chain risk as well. However, from the aforementioned core characteristics those measures most often address the deviation from efficiency-based objectives. Purely cost- and waste-considering objectives, however, evaluate supply chain's performance in retrospect. They miss to assess both operational effectiveness and important strategic achievements like product quality and customer satisfaction [83]. When it is not possible to fully quantify supply chain risk through risk measures, still supply chain risk and its related core characteristics need to be represented within supply chain models. Despite numerous approaches relevant research gaps have been identified:

- As nowadays supply chains need to fulfill efficiency- and effectiveness-driven objectives, approaches should account for balancing these opposite requirements, for example balancing distribution costs and shipment rates, or overall logistics costs and service level, see Section 4.1.
- More advanced (context-sensitive) approaches especially with respect to the risk attitude of the decision maker and with respect to the environment of the affected supply chain are needed, see Sections 4.2 and 4.3.
- The impact of time-aspects is evident, their integration into quantitative models, however, challenging, see Section 4.2.3.

Besides categorizing available approaches and identifying research gaps, the underlying review clarified the meaning and importance of notions commonly used within the (supply chain) risk management literature.

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References

- [1] Iso 14971:2007 – medical devices—application of risk management to medical devices, Accessed July, 2014.
- [2] Aarrow Kenneth J. Risk perception in psychology and economics. *Economic Inquiry* 1982;20:1–9.
- [3] Acerbi C, Tasche D. On the coherence of expected shortfall. *Journal of Banking and Finance* 2002;26:1487–503.
- [4] Azaron A, Brown KN, Tarim SA, Modarres M. A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal of Production Economics* 2008;116(1):129–38.
- [5] Bañuls Víctor A, Turoff Murray. Scenario construction via Delphi and cross-impact analysis. *Technological Forecasting and Social Change* 2011;78(9):1579–602.
- [6] Babazadeh Reza, Razmi Jafar. A robust stochastic programming approach for agile and responsive logistics under operational and disruption risks. *International Journal of Logistics Systems and Management* 2012;13(4):458–82.
- [7] Baghalian Atefeh, Rezapour Shabnam, Farahani Reza Zanjirani. Robust supply chain network design with service level against disruptions and demand uncertainties: a real-life case. *European Journal of Operational Research* 2013;227(1):199–215.
- [8] Barnes Paul, Oloruntoba Richard. Assurance of security in maritime supply chains: conceptual issues of vulnerability and crisis management. *Journal of International Management* 2005;11:519–40.
- [9] Baron DP. On the utility-theoretic foundation of mean-variance analysis. *Journal of Finance* 1977;32(5):1683–97.
- [10] Barroso AP, Machado VH, Machado V Cruz. Identifying vulnerabilities in the supply chain. In: IEEE international conference on industrial engineering and engineering management, 2009. IEEM 2009; IEEE, 2009. p. 1444–48.
- [11] Basel Committee on Banking Supervision. International convergence of capital measurement and capital standards. Technical report, Bank for international settlements, 2004. ISBN: 92-9131-669-5.
- [12] Beamon Benita M. Supply chain design and analysis: models and methods. *International Journal of Production Economics* 1998;55(3):281–94.
- [13] Bell D. Measuring risk and return of portfolios. In: Wise choices. HBS Publishing; 1996.
- [14] Ben-Tal Aharon, Chung Byung Do, Mandala Supreet Reddy, Yao Tao. Robust optimization for emergency logistics planning: risk mitigation in humanitarian relief supply chains. *Transportation Research Part B: Methodological* 2011;45(8):1177–89.
- [15] Berdica Katja. An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy* 2002;9(2):117–27.
- [16] Bernstein Peter L. Against the gods: the remarkable story of risk. New York: John Wiley; 1998.
- [17] Birkmann Jörn. Measuring vulnerability to promote disaster-resilient societies: conceptual frameworks and definitions. In: Measuring vulnerability to natural hazards; TERI, New Delhi, 2006. p. 9–53.
- [18] Boin Arjen, McConnell Allan. Preparing for critical infrastructure breakdowns: the limits of crisis management and the need for resilience. *Journal of Contingencies and Crisis Management* 2007;15(1):50–9.
- [19] Borgström B. Exploring efficiency and effectiveness in the supply chain: a conceptual analysis. In: Proceedings from the twenty-first IMP conference, Rotterdam, Netherlands; 2005.
- [20] Breakwell Glynis Marie. *The psychology of risk*. Cambridge: Cambridge University Press; 2007.
- [21] Viceira, Luis M., and John Y. Campbell. *Strategic Asset Allocation: Portfolio Choice for Long-Term Investors*. Oxford University Press, 2002.
- [22] Cardona Omar. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. In: Bankoff G, Frerik G, Hillhorst D, editors. *Mapping vulnerability: disasters, development and people*. London, UK: Earthscan Publications; 2004. p. 37–51.
- [23] Helena Carvalho and V. Cruz-Machado (2011). Integrating Lean, Agile, Resilience and Green Paradigms in Supply Chain Management (LARG_SCM), Supply Chain Management, Dr. pengzhong Li (Ed.), ISBN: 978- 953-307-184-8, InTech, Available from: <http://www.intechopen.com/books/supply-chain-management/integrating-lean-agile-resilience-and-green-paradigms-in-supply-chain-management-larg-scm->.
- [24] Cavinato JL. Supply chain logistics risks. *International Journal of Physical Distribution & Logistics Management* 2004;34(5):383–7.
- [25] Chapman Paul, Christopher Martin, Jüttner Uta, Peck Helen, Wilding Richard. Identifying and managing supply-chain vulnerability. *Logistics & Transport Focus* 2002;4(4):59–64.
- [26] Chen FY, Yano CA. Improving supply chain performance and managing risk under weather-related demand uncertainty. *Management Science* 2010;56(8):1380–97.
- [27] Chermack Thomas J. Improving decision-making with scenario planning. *Futures* 2004;36(3):295–309.
- [28] Chopra S, Sodhi MMS. Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review* 2004;46(1):53–61.
- [29] Christopher M, Lee H. Supply chain confidence: the key to effective supply chains through improved visibility and reliability. Technical report, Cranfield University and Stanford University; 2001.

- [30] Christopher Martin, Peck Helen. Building the resilient supply chain. *International Journal of Logistics Management* 2004;15(2):1–13.
- [31] Coleman L. Frequency of man-made disasters in the 20th century. *Journal of Contingencies and Crisis Management* 2006;15:1–13.
- [32] Comes Tina, Hiete Michael, Wijngaards Niek, Schultmann Frank. Decision Maps: A framework for multi-criteria decision support under severe uncertainty. *Decision Support Systems* 2011;52(1):108–18.
- [33] Comfort Louise K. Crisis management in hindsight: cognition, communication, coordination, and control. *Public Administration Review* 2007;67:189–97.
- [34] Cox DF. Risk-taking and information-handling in consumer behavior. Boston: Harvard University Press; 1967.
- [35] Cox LA. Why risk is not variance: an expository note. *Risk Analysis* 2008;28(4):925–8.
- [36] Craighead CW, Blackhurst J, Rungtusanatham MJ, Handfield RB. The severity of supply chain disruptions: design characteristics and mitigation capabilities. *Decision Sciences* 2007;38:131–56.
- [37] Cui Tingting, Ouyang Yanfeng, Shen Zuo-JunMax. Reliable facility location design under the risk of disruptions. *Operations Research* 2010;58(4-part-1):998–1011.
- [38] Kahneman Amos, Tversky Daniel. Prospect theory: an analysis of decision under risk. *Econometrica* 1979;47(2):263–92.
- [39] de Finetti B. Il problema dei pieni. *Giornale dell'Istituto Italiano degli Attuari* 1940;11:1–88.
- [40] DNV - Det Norske Veritas. Risk—a word from ancient Greece; 2012.
- [41] Ellis Scott C, Henry Raymond M, Shockley Jeff. Buyer perceptions of supply disruption risk: a behavioral view and empirical assessment. *Journal of Operations Management* 2010;28(1):34–46.
- [42] Falasca Mauro, Zobel Christopher W, Cook Deborah. A decision support framework to assess supply chain resilience. In: Friedrich F, Van de Walle B. (Eds.), 5th ISCRAM conference, Washington, DC, USA; 2008. p. 596–605.
- [43] Fang J, Zhao L, Fransoo JC, Van Woensel T. Sourcing strategies in supply risk management: an approximate dynamic programming approach. *Computers and Operations Research* 2013;40(5):1371–82.
- [44] Federgruen Awi, Yang Nan. Optimal supply diversification under general supply risks. *Operations Research* 2009;57(6):1451–68.
- [45] Fishburn Peter C. Foundations of risk measurement. I. risk as probable loss. *Management Science* 1984;30(4):396–406.
- [46] Simon French. Cynefin, statistics and decision analysis. *Journal of the Operational Research Society* 64, 2012, 547–561.
- [47] Frosdick M. The techniques of risk management are insufficient in themselves. *Disaster Prevention and Management* 1997;6(3):165–77.
- [48] Gan Boon Ping, Liu Li, Jain Sanjay, Turner Stephen J, Cai Wentong, Hsu Wen-Jing. Manufacturing supply chain management: distributed supply chain simulation across enterprise boundaries. In: Proceedings of the thirty-second conference on Winter simulation, San Diego, CA, USA, Society for Computer Simulation International; 2000. p. 1245–51.
- [49] Glickmann TS, White SC. Security, visibility and resilience: the keys to mitigating supply chain vulnerabilities. *International Journal of Logistics Systems and Management* 2006;2(2):10–119.
- [50] Goh M, Lim JYS, Meng F. A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research* 2007;182(1):164–73.
- [51] Gollier Christian. The economics of risk and time. MIT Press; 2004.
- [52] Götz U, Mikus B. Der prozess des risikomanagements in supply chains. In: Vahrenkamp R, Siepermann C, editors. *Risikomanagement in supply chains*. Berlin: Erich Schmidt Verlag GmbH & Co.; 2007. p. 29–58.
- [53] Grundy SM, Pasternak R, Greenland P, Smith S, Fuster V. Assessment of cardiovascular risk by use of multiple-risk-factor assessment equations: a statement for healthcare professionals from the american heart association and the american college of cardiology. *Journal of the American College of Cardiology* 1999;34(4):1348–59.
- [54] Gurnani Hareesh, Mehrotra Anuj, Ray Saibal, editors. *Supply chain disruptions: theory and practice of managing Risk*. Springer; 2011.
- [55] Hahn GJ, Kuhn H. Value-based performance and risk management in supply chains: a robust optimization approach. *International Journal of Production Economics* 2012;139(1):135–44.
- [56] Haimes Yacov Y, Kaplan Stan, Lambert James H. Risk filtering, ranking, management framework using hierarchical holographic modeling. *Risk Analysis* 2002;22(2):383–98.
- [57] Hämäläinen Raimo P, Lindstedt Mats RK, Sinkko Kari. Multiattribute risk analysis in nuclear emergency management. *Risk Analysis* 2000;20(4):455–68.
- [58] Helbing Dirk, Ammoser Hendrik, Kühnert Christian. Disasters as extreme events and the importance of network interactions for disaster response management. In: Albeverio Sergio, Jentsch Volker, Kantz Holger, editors. *Extreme events in nature and society, the frontiers collection*. Berlin Heidelberg: Springer; 2006. p. 319–48.
- [59] Helbing Dirk, Lämmer Stefan. Managing complexity: an introduction. In: Helbing D, editor. *Managing complexity: insights, concepts, applications understanding complex systems*, vol. 32. Berlin, Heidelberg: Springer; 2008. p. 1–16.
- [60] Hodges Alan. Emergency risk management. *Risk Management* 2000;2(4):7–18.
- [61] Håkansson Håkan, Prenkert Frans. Exploring the exchange concept in marketing. In: *Rethinking Marketing—developing a new understanding of markets*. Håkan Håkansson & Alexandra Waluszewski; 2004.
- [62] Huang Edward, Goetschalckx Marc. Strategic robust supply chain design based on the pareto-optimal tradeoff between efficiency and risk. *European Journal of Operational Research* 2014;237(2):508–18.
- [63] Hull John. Options, futures, and other derivatives. 6th ed. Upper Saddle River, NJ: Pearson, Prentice Hall; 2006.
- [64] Hull John. Risk management and financial institutions. John Wiley and Sons; 2012.
- [65] Jenelius Erik, Mattsson Lars-Gran. Road network vulnerability analysis of area-covering disruptions: a grid-based approach with case study. *Transportation Research Part A: Policy and Practice* 2012;46(5):746–60.
- [66] Jüttner U, Maklan S. Supply chain resilience in the global financial crisis: an empirical study. *Supply Chain Management* 2011;16(4):246–59.
- [67] Jüttner U, Peck H, Christopher M. Supply chain risk management: outlining an agenda for future research. *International Journal of Logistics Research and Applications* 2003;6(4):197–210.
- [68] Jüttner Uta. Supply chain risk management: understanding the business requirements from a practitioner perspective. *The International Journal of Logistics Management* 2005;16(1):120–41.
- [69] Peter. Kajüter, Instrumente zum Risikomanagement in der Supply Chain. In: *Supply chain controlling in theorie und praxis*. Wolfgang Stizle und Andreas Otto; 2003.
- [70] Kajüter Peter. Risikomanagement in der Supply Chain: Ökonomische, regulatorische und konzeptionelle Grundlagen. In: Vahrenkamp Richard, Siepermann Christoph, editors. *Risikomanagement in supply chains*. Berlin: Erich Schmidt Verlag GmbH & Co.; 2007. p. 13–27.
- [71] Kersten W, Held T, Meyer CM, Hohrath P. Komplexitäts- und Risikomanagement als Methodenbausteine des Supply Chain Managements, In: *Management am Puls der Zeit – Strategien, Konzepte und Methoden*. I. Hausladen & C. Mauch; 2007.
- [72] Kersten Wolfgang, Bger Mareike, Hohrath Philipp, Späth Hagen. Supply chain risk management: development of a theoretical and empirical framework. In: Kersten Wolfgang, Blecker Thomas, editors. *Managing risks in supply chains - how to build reliable collaboration in logistics*. Berlin: Erich Schmidt Verlag GmbH & Co.; 2006. p. 3–18.
- [73] Klibi W, Martel A. Scenario-based supply chain network risk modeling. *European Journal of Operational Research* 2012;223:644–58.
- [74] Klinken Andreas, Renn Ortwin. A new approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies. *Risk Analysis* 2002;22(6):1071–94.
- [75] Knight F. Risk, uncertainty, and profits. Hart, Schaffner, and Marx; 1921.
- [76] Kovacs George L, Paganelli Paolo. A planning and management infrastructure for large, complex, distributed projects—beyond ERP and SCM. *Computers in Industry* 2003;51(2):165–83.
- [77] Kuhn AM, Youngberg BJ. The need for risk management to evolve to assure a culture of safety. *Quality and Safety in Health Care* 2002;11(2):158–62.
- [78] Kull T, Closs D. The risk of second-tier supplier failures in serial supply chains: implications for order policies and distributor autonomy. *European Journal of Operational Research* 2008;186(3):1158–74.
- [79] Kumar Sri Krishna, Tiwari MK, Babiceanu Radu F. Minimisation of supply chain cost with embedded risk using computational intelligence approaches. *International Journal of Production Research* 2010;48(13):3717–3739.
- [80] Kupsch P. Risikomanagement. In: Corsten, H., Reiß, M. *Handbuch unternehmensführung. konzepte - instrumente - schnittstellen*; 1995.
- [81] Lai Guoming, Debo Laurens G, Sycara Katia. Sharing inventory risk in supply chain: the implication of financial constraint. *Omega* 2009;37(4):811–25.
- [82] Landsman Z, Sherris M. Risk measures and insurance premium principles. *Insurance: Mathematics and Economics* 2001;29(1):103–15.
- [83] Lapidé Larry. What about measuring supply chain performance? *Achieving Supply Chain Excellence Through Technology* 2000;2:287–97.
- [84] Lempert Robert J, Groves David G. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the american west. *Technological Forecasting and Social Change* 2010;77(6):960–74.
- [85] Liu Zugang, Nagurney Anna. Supply chain outsourcing under exchange rate risk and competition. *Omega* 2011;39(5):539–49.
- [86] Lockamy III Archie, McCormack Kevin. Analysing risks in supply networks to facilitate outsourcing decisions. *International Journal of Production Research* 2010;48(2):593–611.
- [87] Mak H, Shen Z. Risk diversification and risk pooling in supply chain design. *IIE Transactions (Institute of Industrial Engineers)* 2012;44(8):603–21.
- [88] Manuj Ila, Mentzer John T. Global supply chain risk management strategies. *International Journal of Physical Distribution and Logistics Management* 2008;38(3):192–223.
- [89] Manyena Siambabala Bernard. The concept of resilience revisited. *Disasters* 2006;30(4):434–50.
- [90] March JG, Shapira Z. Managerial perspectives on risk and risk taking. *Management Science* 1987;33(11):1404–18.
- [91] Markowitz Harry. Portfolio selection. *The Journal of Finance* 1952;7(1):77–91.
- [92] McNeil Alexander J, Rüdiger Frey, Embrechts Paul. Quantitative risk management: concepts, techniques and tools. Princeton University Press; 2005.
- [93] Melo MT, Nickel S, Saldanha-da-Gama F. Facility location and supply chain management—a review. *European Journal of Operational Research* 2009;196:401–12.
- [94] Merriam-Webster, 2013.
- [95] Merz Mirjam, Hiete Michael, Comes Tina, Schultmann Frank. A composite indicator model to assess natural disaster risks in industry on a spatial level. *Journal of Risk Research* 2013;16(9):1077–99.

- [96] Kristian KE, Möller, Törrönen Pekka. Business suppliers' value creation potential: a capability-based analysis. *Industrial Marketing Management* 2003;32(2):109–18.
- [97] Granger Millet, Morgan A, Henrion Max. *Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge: Cambridge University Press; 1990.
- [98] Mula Josefa, Peidro David, Díaz-Madro nero Manuel, Vicens Eduardo. Mathematical programming models for supply chain production and transport planning. *European Journal of Operational Research* 2010;204(3):377–90.
- [99] Murray AT, Grubescic TH, editors. *Reliability and vulnerability in critical infrastructure: a quantitative geographic perspective*. Springer; 2006.
- [100] Nagurney Anna, Cruz Jose, Dong June, Zhang Ding. Supply chain networks, and supply side and demand side risk. *European Journal of Operational Research* 2005;164(1):120–42.
- [101] Norrman A, Jansson J, Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident. *International Journal of Physical Distribution and Logistics Management* 2004;35(5):434–53.
- [102] Oliveira F, Gupta V, Hamacher S, Grossmann IE. A lagrangean decomposition approach for oil supply chain investment planning under uncertainty with risk considerations. *Computers and Chemical Engineering* 2013;50:184–95.
- [103] Owen SH, Daskin MS. Strategic facility location: a review. *European Journal of Operational Research* 1998;111:423–47.
- [104] Peck H. Drivers of supply chain vulnerability: an integrated framework. *International Journal of Physical Distribution & Logistics Management* 2005;35(4):210–32.
- [105] Peck H. Reconciling supply chain vulnerability, risk and supply chain management. *International Journal of Logistics Research and Applications* 2006;9(2):127–42.
- [106] Pedersen CS, Satchell SE. Choosing the right risk measure: a survey. Technical report, Available at ([http://citeseer.ist.psu.edu/52\(0923\).html](http://citeseer.ist.psu.edu/52(0923).html)); 1998.
- [107] Peng M, Peng Y, Chen H. Post-seismic supply chain risk management: a system dynamics disruption analysis approach for inventory and logistics planning. *Computers and Operations Research* 2014;42:14–24.
- [108] Petak William J. Emergency management: a challenge for public administration. *Public Administration Review* 1985;45:3–7.
- [109] Pettit Timothy J, Fiksel Joseph, Croxton Keely L. Ensuring supply chain resilience: development of a conceptual framework. *Journal of Business Logistics* 2010;31(1):1–21.
- [110] Ponomarev SY, Holcomb MC. Understanding the concept of supply chain resilience. *International Journal of Logistics Management* 2009;20(1):124–43.
- [111] Poojari CA, Lucas C, Mitra G. Robust solutions and risk measures for a supply chain planning problem under uncertainty. *Journal of the Operational Research Society* 2008;59(1):2–12.
- [112] Quansah Joseph E, Engel Bernard, Rochon Gilbert L. Early warning systems: a review. *Journal of Terrestrial Observation* 2010;2(2):24–44.
- [113] Renda Andrea. Protecting critical infrastructure in the EU. CEPS task force report, Centre for European Studies, Brussels, 2010.
- [114] Rice JB, Caniato F. Building a secure and resilient supply network. *Supply Chain Management Review* 2003;7(5):22–30.
- [115] Richey Jr R Glenn. The supply chain crisis and disaster pyramid: a theoretical framework for understanding preparedness and recovery. *International Journal of Physical Distribution & Logistics Management* 2009;39(7):619–28.
- [116] Risk Response Network. New models for addressing supply chain and transport risk. Technical report, The World Economic Forum, 2011.
- [117] Risk Response Network. Building resilience in supply chains. Technical report, The World Economic Forum, 2013.
- [118] Rockafellar R Tyrrel, Uryasev Stanislav. Optimization of conditional value-at-risk. *Journal of Risk* 2000;2:21–42.
- [119] Rosenhead J, Elton M, Gupta S. Robustness and optimality as criteria for strategic decisions. *Operational Research Quarterly* 1972;23(4):413–30.
- [120] Ross Ivan. Perceived risk and consumer behavior: a critical review. *Advances in Consumer Research* 1975;2(1):1–20.
- [121] Sarykalin S, Serraino G, Uryasev S. Value-at-risk vs. conditional value-at-risk in risk management and optimization. In: *Tutorials in operations research, INFORMS*; 2008. p. 270–94.
- [122] Sahebi Hadi, Nickel Stefan, Ashayeri Jalal. Strategic and tactical mathematical programming models within the crude oil supply chain context. *Computers and Chemical Engineering* 2014;68:56–77.
- [123] Sawik T. Integrated selection of suppliers and scheduling of customer orders in the presence of supply chain disruption risks. *International Journal of Production Research* 2013;51(23–24):7006–22.
- [124] Sawik T. Optimization of cost and service level in the presence of supply chain disruption risks: Single vs. multiple sourcing. *Computers and Operations Research* 2014;51:11–20.
- [125] Sawik Tadeusz. Selection of supply portfolio under disruption risks. *Omega* 2011;39(2):194–208.
- [126] Schmitt AJ, Singh M. A quantitative analysis of disruption risk in a multi-echelon supply chain. *International Journal of Production Economics* 2012;139(1):22–32.
- [127] Sheffi Y. *The resilient enterprise*. The MIT Press; 2007.
- [128] Sheffi Y, Rice B. A supply chain view of the resilient enterprise. Technical report, MIT Sloan Management review; 2005.
- [129] Simchi-Levi D, Kaminsky P, Simchi-Levi E. *Designing and managing the supply chain*. New York: McGraw-Hill/Irwin; 2008.
- [130] Simchi-Levi David. *Operations rules*. MIT Press; 2010.
- [131] Singhal Piyush, Agarwal Gopal, Mittal Murali Lal. Supply chain risk management: review, classification and future research directions. *International Journal of Business Science and Applied Management* 2011;6(3):15–42.
- [132] Smith JC. Basic interdiction models. *Wiley Encyclopedia of Operations Research and Management Science*; 2010.
- [133] Snyder Lawrence V, Atan Zumbul, Peng Peng, Rong Ying, Schmitt Amanda J, Sinoysal Burcu. Or/ms models for supply chain disruptions: a review. Available at SSRN 1689882; 2012.
- [134] Sodhi MS. Managing demand risk in tactical supply chain planning for a global consumer electronics company. *Production and Operations Management* 2005;14(1):69–79.
- [135] Sodhi ManMohan S, Son Byung-Gak, Tang Christopher. Researchers perspective on supply chain risk management. *Production and Operations Management* 2012;21(1):1–13.
- [136] Sodhi ManMohan S, Tang Christopher. Managing supply chain disruptions via time-based risk management. In: Wu Teresa, Blackhurst Jennifer, editors. *Managing supply chain risk and vulnerability—tools and methods for supply chain decision makers*. Springer; 2009.
- [137] Soleimani H, Govindan K. Reverse logistics network design and planning utilizing conditional value at risk. *European Journal of Operational Research*; 2014, in Press.
- [138] Stock J, Boyer S. Developing a consensus definition of supply chain management: a qualitative study. *International Journal of Physical Distribution & Logistics Management* 2009;39(8):690–711.
- [139] Supply Chain Digest. The greatest supply chain disasters of all time 2009. Technical report, Supply Chain Digest, 2009.
- [140] Svensson G. A conceptual framework for the analysis of vulnerability in supply chains. *International Journal of Physical Distribution & Logistics Management* 2000;30(9):731–50.
- [141] Svensson G. Dyadic vulnerability in companies' inbound and outbound logistics flows. *Journal of Logistics: Research and Applications* 2002;5(1):81–113.
- [142] Svensson G. Vulnerability in business relationships: the gap between dependence and trust. *Journal of Business & Industrial Marketing* 2004;19(7):469–83.
- [143] Tang Ou, Musa S Nurmaya. Identifying risk issues and research advancements in supply chain risk management. *International Journal of Production Economics* 2011;133(1):25–34.
- [144] Tang S. Perspectives in supply chain risk management. *International Journal of Production Economics* 2006;103:451–88.
- [145] Tang S. Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics* 2006;9:33–45.
- [146] Tomlin Brian. On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science* 2006;52(5):639–57.
- [147] United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR). *Living with risk: a global review of disaster reduction initiatives, volume II*. United Nations publication, New York and Geneva; 2004.
- [148] Van de Walle Bartel, Turoff Murray. Decision support for emergency situations. *Information Systems and E-Business Management* 2008;6(3):295–316.
- [149] Vanany I, Zailani S, Pujawan N. Supply chain risk management: literature review and future research. *International Journal of Information Systems and Supply Chain Management* 2009;2(1):16–33.
- [150] Wagner S, Bode C. An empirical investigation into supply chain vulnerability. *Journal of Purchasing and Supply Management* 2006;12(6):301–12.
- [151] Wagner SM, Bode C. An empirical examination of supply chain performance along several dimensions of risk. *Journal of Business Logistics* 2008;29:307–25.
- [152] Wagner Stephan M, Bode Christoph. Dominant risks and risk management practices in supply chains. In: Zsidisin George A, Ritchie Bob, editors. *Supply chain risk, international series in operations research & management science, vol. 124*. Springer; 2009. p. 271–90.
- [153] Wakolbinger T, Cruz JM. Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts. *International Journal of Production Research* 2011;49(13):4063–84.
- [154] Waters D. *Supply chain risk management*. Kogan Page Limited; 2007.
- [155] Wu D, Olson DL. Supply chain risk, simulation, and vendor selection. *International Journal of Production Economics* 2008;114(2):646–55.
- [156] Wu Y. Robust optimization applied to uncertain production loading problems with import quota limits under the global supply chain management environment. *International Journal of Production Research* 2006;44(5):849–82.
- [157] You Fengqi, Wassick John M, Grossmann Ignacio E. Risk management for a global supply chain planning under uncertainty: models and algorithms. *AIChE Journal* 2009;55(4):931–46.
- [158] Yu H, Zeng AZ, Zhao L. Single or dual sourcing: decision-making in the presence of supply chain disruption risks. *Omega* 2009;37(4):788–800.
- [159] Yu M, Goh M. A multi-objective approach to supply chain visibility and risk. *European Journal of Operational Research* 2014;233(1):125–30.
- [160] ArneZiegenbein, Supply Chain Risiken: Identifikation, Bewertung und Steuerung, vol. 15, 2007, vdf Hochschulverlag AG Zürich.
- [161] Zimmermann H-J. An application-oriented view of modeling uncertainty. *European Journal of Operational Research* 2000;122:190–8.
- [162] Zsidisin George A. A grounded definition of supply risk. *Journal of Purchasing and Supply Management* 2003;9(5):217–24.