

# Chapter 5

## Resilience Assessment in Complex Supply Networks



Mustafa Güller and Michael Henke

### 1 Introduction

In today's business environment, the local marketing strategy is shifting away to modern value chains which span the entire globe. However, the opportunities created by the globalization of supply chains bring new challenges. With globalization, supply chains have become more vulnerable to disruptions (Tang and Tomlin 2008). As the network extends over the entire globe, the number of links interconnecting companies is growing significantly. These links are often prone to disruptions, bankruptcies, breakdowns, and disasters, increasing the possibility for unplanned events (Manuj and Mentzer 2008). Furthermore, the structure of supply chains is shifting away from the "chain structure" toward "a network of interacting entities." Hence, a supply network can be considered as a network of (semi)autonomous organizations that make decisions independently. These organizations usually work in a distributed and decentralized manner in such a complex network (Chan and Chan 2010; Hongler et al. 2010). The increasing length of networks, in conjunction with nonlinear and dynamic interactions between nodes, adds a new level of complexity to the decision-making process. Even though they follow simple local rules, they generate complex patterns of decisions due to relationships among them (Nair et al. 2009). One major problem in such networks is to manage and mitigate risks across multiple independent organizations.

Risks can cause negligible problems like a short delay of a transport or, at the other end of the spectrum, a total breakdown of the entire supply chain (SC) net-

---

M. Güller (✉)  
TU Dortmund University, Dortmund, Germany  
e-mail: [guller@lfo.tu-dortmund.de](mailto:guller@lfo.tu-dortmund.de)

M. Henke  
TU Dortmund University, Fraunhofer Institute for Material Flow and Logistics IML, Dortmund, Germany  
e-mail: [michael.henke@iml.fraunhofer.de](mailto:michael.henke@iml.fraunhofer.de)

© Springer Nature Switzerland AG 2019  
G. A. Zsidisin and M. Henke (eds.), *Revisiting Supply Chain Risk*, Springer Series in Supply Chain Management 7, [https://doi.org/10.1007/978-3-030-03813-7\\_5](https://doi.org/10.1007/978-3-030-03813-7_5)

work due to a natural disaster. More recently, two natural disasters in Asia, the 2011 Tohoku earthquake in Japan and the severe flooding during the monsoon season in Thailand, caused serious disruptions in a number of industries (e.g., the automotive and electronics industries). Such risks may occur at any node in the network and affect other business partners due to interdependencies in flows of goods, financial flows, and flows of information. This motivates firms to rethink their understanding of the structure and interlinkages of their supply networks. Another example is the flood caused by Hurricane Floyd in North Carolina which flooded a Daimler Chrysler plant located in Greenville that is responsible for manufacturing automotive components. As a result, seven assembly plants across North America had to be shut down for seven days (Jüttner 2005). From the aforementioned examples, it can be realized that suppliers are inevitable sources of external risks in any supply network (Rajesh and Ravi 2015), particularly for firms that operate internationally. The results of a recent survey (Snell 2010) illustrated that 90% of firms felt threatened by supply-side risks. However, 60% of the firms noted that they were not confident or knowledgeable enough in managing these risks. Most firms face the risk of disruption to their supply due to accidents at supplier facilities, bankruptcy of a key supplier, labor strikes, defective parts or components, natural disasters, terrorism, or other events. Despite the diversity of causes, supply risks generally fall into three categories: the disruption of supply caused by low likelihood events such as natural disasters or terroristic activities, random yield due to capacity and quality issues, and price volatility resulting from fluctuating exchange rates (Tomlin and Synder 2008).

Resilience has been widely used as one of the core elements to deal with and to respond to such major disruptions. Therefore, building resilient supply networks has become an important issue for managers, stakeholders, and researchers (Kleindorfer and Saad 2005; Ponoramov and Holcomb 2009). Despite a large body of the literature on resilience, there is no generally accepted or generalized standard for measuring resilience of complex systems (Kamalahmadi and Parast 2016; Spiegler et al. 2012). Spiegler et al. conclude from a literature review that most existing studies have proposed qualitative methods in which resilience metrics depend on personal judgment by managers. These qualitative methods are not suitable for investigating ‘what if’ scenarios” and none have focused on exploring the impact of multiple strategies on resilience. According to Kamalahmadi and Parast (2016), one research gap is how firms can choose between different strategies using analytical tools and how the level of resilience of a system can be defined quantitatively. This chapter aims to develop a concept that combines quantitative and qualitative resilience elements in order to calculate a score for supply chain resilience. With such a concept, it could be possible to compare supply chains and companies with regard to their resilience level.

## 2 Supply Chain Resilience

The high number of sources of complexity exposes the network to an increasing level of uncertainty, and the uncertainty level exposes the network to numerous kinds of

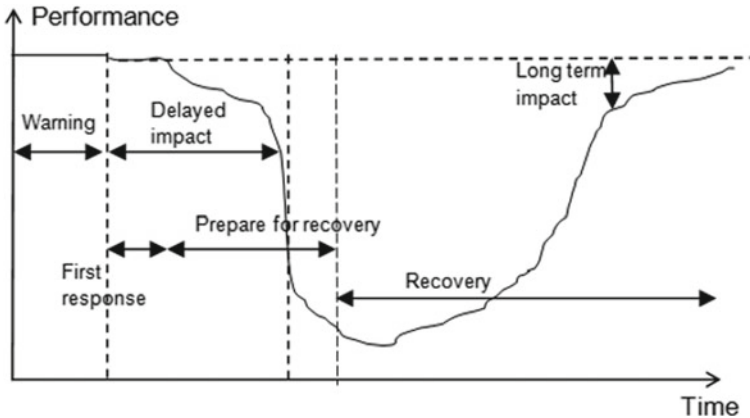
events creating a potential for unpredictable disruptions (Güller et al. 2015). The occurrence of these events is usually random and has a probability of occurrence because not every future event or circumstance can be predicted. Even if the best forecasting methods are used, there will always be a certain degree of uncertainty. Zsidisin (2003) gives a suitable definition for the term “risk” in the supply chain context as “the potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety.” Managing uncertainties leading to risks is always a challenge that requires the ability to survive and adapt in the face of turbulent change. Hence, risk management has become an essential part of management decision and control in supply chains. Another way to respond to such major supply chain disruptions is to build a resilient supply chain. In the supply chain literature, resilience is essentially defined as the ability of a system to return to its original state or move to a new, more desirable state after being disturbed (Christopher and Peck 2004). More recently, Ponomarov and Holcomb (2009) define resilience as “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at desired levels of connectedness and control over structure and function.” In contrast to prior perception, their definition includes the aspect of preparation. According to Klibi (2010), the concept of resilience also implies the avoidance of threatening disturbances. Hohenstein et al. (2015) found 46 different definitions in their systematic literature review. A few of them are:

- “The ability of a system to return to its original state or move to a new, more desirable state after being disturbed” (Christopher and Peck 2004).
- “Resilience ensures that the supply chain can recover quickly and cost-effectively from disruptions caused by natural disasters (such as earthquakes), social factors (employee strikes), medical emergencies (epidemics such as H1N1 flu), economic setbacks (the bankruptcy of a critical link in the chain) or technological failures (a software crisis)” (Melnyk et al. 2014).
- “Supply chain resilience is concerned with the system’s ability to return to its original state or to a new, more desirable, one after experiencing a disturbance, and avoiding the occurrence of failure modes” (Carvalho et al. 2012).
- “Resilience [...] focuses on the ability of the firm to sustain operation and recovery quickly in the face of a disruption” (Schmitt and Singh 2012).
- “Resilience—the ability to survive, adapt, and grow in the face of turbulent change” (Petit et al. 2013).
- “A supply chain can [...] be resilient if its original stable situation is sustained or if a new stable situation is achieved. In this research, resilience is understood as the ability of a supply chain to cope with change” (Wieland and Wallenburg 2013).

In the supply chain literature, several terms are linked with resilience, such as agility, flexibility, and robustness. These terms either complement the topic of resilience or are used interchangeably with it. For example, some researchers argue that robustness is part of a successful implementation of resilience, whereas others

state that these two terms represent two different concepts. Christopher and Peck (2004) and Mandal (2012) state that resilience and robustness are terms used interchangeably in practice. A robust system has the ability to absorb a disturbance while retaining the same previous state, whereas a resilient system has the ability to adapt and achieve a new stable state (Asbjornslett 2008). This leads to the conclusion that robustness may be desirable but is not synonymous with a resilient supply chain. Sheffi (2004) emphasizes that supply chain agility is the ability to respond to unanticipated changes. According to Swafford et al. (2006), agility is defined as the supply chain's capability to respond quickly to short-term changes in demand (or supply) and environment. Most research articles of the existing literature claim that speed and flexibility are two important components of the supply chain agility. The concepts of flexibility and agility are therefore tightly coupled with supply chain resilience (Güller et al. 2015). Wieland and Wallenburg (2013) define resilience with two dimensions: agility, resulting from visibility and speed, and robustness, resulting from anticipation and preparedness. Christopher and Peck (2004) define agility as the third element of supply chain resilience. According to Longo and Ören (2008), the most important elements affecting supply chain resilience are: flexibility, agility, velocity, visibility, and redundancy. Based on the literature review, Lotfi et al. (2013) illustrate some overlapping and non-overlapping practices/initiatives across robustness, agility, and resilience. Consequently, resilience can be achieved through robustness, flexibility, and agility. In the context of robustness, redundant capacity is installed. It is an additional capacity that would be used to replace the capacity loss caused by a disruption. In this regard, flexibility entails redeploying previously committed capacity (Rice and Caniato 2003). On the other hand, instead of being prepared for every situation by creating a robust supply chain, it is much more appreciated to increase the flexibility of the supply chain to adapt quickly and efficiently to changes.

The process of a disruption can be categorized in different phases, as illustrated in Fig. 1. As disruptions may or may not occur, firms can take measures before and after an unforeseeable event in order to be resilient. Thus, according to Melnyk et al. (2014), actions that aim to avoid shocks or to be prepared for them are referred to as "resistance capacity," whereas "recovery capacity" is the ability to restore operations after a disruption has occurred. The difference between the two elements of "resistance" is that one refers to preventing disruptions entirely (avoidance) and the other to shortening the time between the start of a disruption and the beginning of the recovery process (containment). The recovery process, in turn, consists of a "stabilization" phase and the "return" to a steady-state performance. The length of stabilization depends on the severity of the disruption. Ponomarov and Holcomb (2009) identify one more phase of supply chain resilience besides resistance and recovery, which is called the response phase. During this phase, a supply chain develops the ability to learn and adapt in response to disturbances. This diagram helps to visualize the magnitude of disturbance impact on the system performance.



**Fig. 1** Different phases of a disruption based on Sheffi (2004)

### 3 Elements of Supply Chain Resilience

In order to understand resilience in supply chains, it is crucial to analyze existing factors that help build resilience. In the current literature, there are many terms for “elements” that are used to achieve resilience. Longo and Ören (2008) use the term elements, whereas Ponomarrow and Holcomb (2009) as well as Scholten et al. (2014) call them antecedents and Soni et al. (2014) use the term enablers (Longo and Ören 2008; Ponomarov and Holcomb 2009). The term capability is used by other authors (Fiksel et al. 2015; Petit et al. 2012).

For instance, Blackhurst et al. (2005) name three elements that manage supply chain disruptions: “disruption discovery,” “disruption recovery,” and “supply chain redesign.” Thus, “discovery” is a capability that is required before the disruption takes place. “Recovery” and “redesign” are essential elements in the time after the disruption occurrence.

Resiliency criteria are used to quantify different aspects of the supply chain resilience (SCRES). The decision support framework for SCRES by Falasca et al. (2008) consists of three major criteria. These are SC density, SC complexity, and the number of critical nodes in an SC. The SC density is defined as “the quantity and geographical spacing of nodes within a supply chain.” The second determinant (SC complexity) is defined as the number of nodes and interconnections between the nodes in an SC. Therefore, a highly complex SC has plenty of nodes and plenty of interconnections between these nodes. The number of critical nodes in an SC is the third determinant and defines specific nodes within an SC and the relative importance of it. Regarding SCR, the connection between these three determinants is described as complex (Falasca et al. 2008).

The elements discussed by Ponomarov and Holcomb (2009) are: agility, responsiveness; visibility; flexibility/redundancy; structure and knowledge; reduction of uncertainty, complexity, reengineering; collaboration; integration, operational capa-

bilities, and transparency. For agility and responsiveness, as well as visibility, the explanations of Christopher and Peck (2004) are used again. Flexibility is again determined as the ability of a company to quickly respond to changed market conditions, but there is also a connection made between redundancy and flexibility.

Petit et al. (2013) created a “supply chain resilience framework” which defines seven vulnerability factors. These vulnerability factors are considered to be the source of changes and are divided into 40 sub-factors. To counter the vulnerability factors, 14 managerial capability factors with 71 sub-factors are introduced. It is important to balance the vulnerabilities and the capabilities because if an SC has a high capability but only a low vulnerability, the profits of an SC erode. On the other hand, if the vulnerability is high but the capability is low, the SC has a high exposure to risks.

Cardoso et al. (2014) developed a “mixed integer linear model” to assess the SCRES. The latest model published in 2015 consists of eleven criteria to measure SCRES which are introduced as indicators. The economic performance is measured in terms of the expected net present value (ENPV). The eleven criteria are divided into three different categories. The first category is “network design indicators” with four criteria and the second category is “network centralization indicators” (Cardoso et al. 2015) also with four criteria. The last category is defined as “operational indicators” and consists of three criteria. The categories network design indicators and network centralization indicators are assessed in contrast to the operational indicators. To test the presented criteria, the authors applied the model to five existing supply chains which all have different designs. They conclude that SCs with a resilient design from the beginning need less mitigation strategies to handle disruptions. Additionally, to measure if an SC is resilient, a decision-making process and a large variety of different scenarios need to be implemented and assessed using simulations (Cardoso et al. 2015).

Soni et al. (2014) identified 14 elements forming supply chain resilience: agility, collaboration, visibility, risk management culture, adaptive capability, risk and revenue sharing, trust among players, information sharing, sustainability, corporate social responsibility, information security, supply chain structure, strategic risk planning, and knowledge sharing. The authors propose graph theory can be used to measure SC resilience. Sustainability is a key enabler for resilience of supply chains because improved understanding of what constitutes sustainability in a supply chain helps managers make better decisions. Hence, the risks of a single company and the whole supply chain are decreased. Risk and revenue sharing enables collaboration between supply chain members and makes it possible to focus on long-term decisions. Sharing benefits with upstream and downstream partners allows the sharing of risks, thus creating a competitive advantage. A precondition for this risk and revenue sharing is trust among the players. Trust diminishes functional conflict, allows greater cooperation, and improves integration and decision-making under uncertain conditions. On the other hand, a lack of trust contributes to supply chain risks. In this context, trust is defined as the expectation that no supply chain partner will act in an opportunistic way, although it might show advantages in the short term. Therefore, trust presents itself as very important for the long-term stability of an organization

and its supply chain. In addition, it makes cooperation and collaboration possible within the organization and with partners.

Scholten et al. (2014) adopt the four elements introduced by Christopher and Peck (2004): supply chain (re)engineering, collaboration, agility, and risk awareness. Additionally, they consider risk awareness/knowledge management as a fifth system-level element. A supportive management culture and direct top management support are needed to establish a resilient supply chain. A part of this is the capacity to learn from past disruptions to improve preparedness for future events. A measure for this can be training for employees, suppliers, and customers about security and supply network risks to raise awareness and reinforce the importance of supply chain resilience.

## 4 A Framework for Resilience Assessment in Supply Networks

After analyzing the existing literature for core elements and measurement approaches to supply network resilience, this section provides a concept for resilience assessment. The presented measurement in the previous section has foundations that are either quantitative, like Spiegler et al. (2012), or qualitative like Petit et al. (2012). The developed concept combines both; some sub-factors can be calculated quantitatively, whereas others cannot. The main framework for resilience assessment is presented in Fig. 2. In order to assign points for each sub-factor, scorecards are developed in the following section. Ratings are either quantitative when possible or qualitative when respectively subjective.

### 4.1 Supply Chain Design

The first factor in the category of interorganizational elements is “supply chain design.” Supply chain complexity, density, and node criticality are identified as significant elements of resilience. Supply chain density and node criticality each have two measures. Hence, five sub-factors are taken into account for the assessment of supply chain resilience (SCRES) regarding the supply chain design.

#### 4.1.1 Supply Chain Density (Average Internode Distance, Number of Critical Nodes)

A dense supply chain is more vulnerable to disruptions than a less dense network. Two measures for assessing the density of a supply chain are average internode distance and number of node areas (Craighead et al. 2007). In this regard, both are

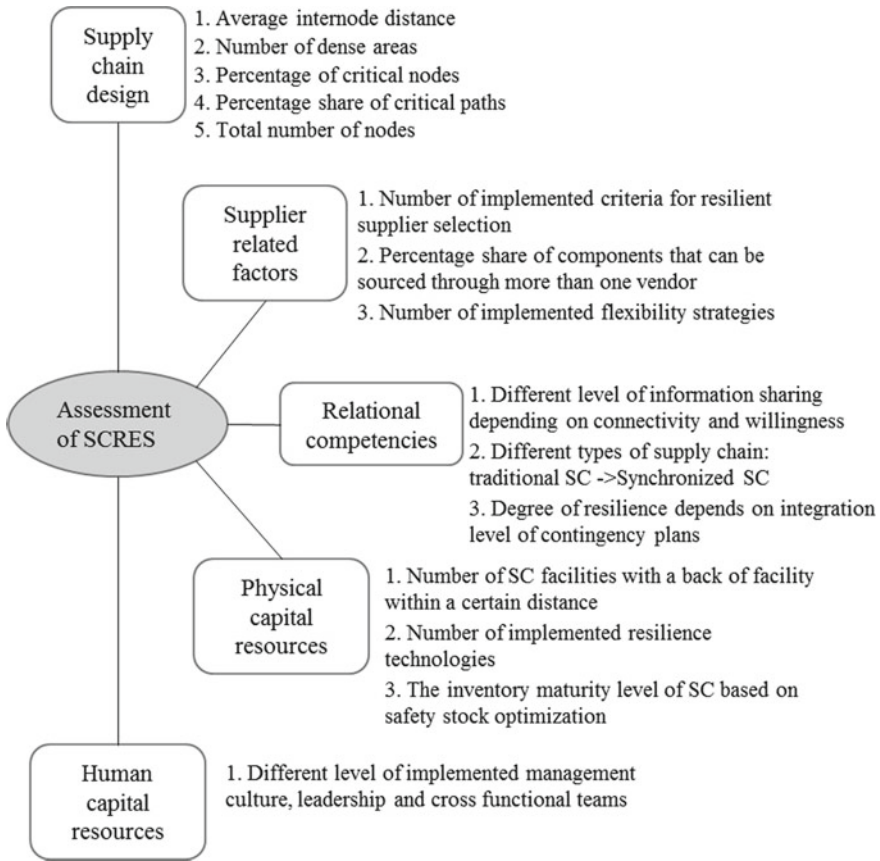


Fig. 2 Summary of approaches for the evaluation of each sub-factor

considered sub-factors. First, for calculating the average internode distance  $d_{\emptyset}$ , the distances  $d(n_{pi})$  of all pair of nodes  $n_p$  have to be added together:

$$d = \sum_{i=1}^{n_{pi}} d(n_{pi}), i = 1 \rightarrow n_p$$

Second, to get the average internode distance  $d_{\emptyset}$ , the overall distance  $d$  has to be divided by the number of all pair of nodes  $n_p$ :

$$d_{\emptyset} = \frac{d}{n_p}$$

The second suggestion of Craighead et al. (2007) is the number of node areas within a supply chain. On first sight, it seems redundant to use both the density



average internode distance and number of dense areas. For example, a supply network with a relatively high-average internode distance is said to be more resilient than a comparable network with a lower-average internode distance, as the latter is denser. However, the structure of both supply chains has to be considered. The former can consist of a few very dense areas that are geographically far away from each other. The high distances between the areas increase the average internode distance, making the supply chain less dense, when considering the entire network. But the existence of many dense areas decreases resilience, and thus, in terms of supply chain design, the supply chain with a higher-average internode distance is not necessarily more resilient than the more balanced supply chain with a lower-average internode distance.

When describing a supply chain through the number of dense areas within it, all the criteria for dense areas have to be defined. Craighead et al. (2007) mention “when entities within a supply chain reside in close proximity to one another within a geographical region, that specific portion of the supply chain (i.e., that region) can be deemed to be densely populated.” Yet, this might not be sufficient for quantitatively assessing the number of dense areas and for further use of it as a sub-factor for measuring SC resilience (SCRES). Either there are clearly defined characteristics or there is a way of calculating whether an area can be considered dense or not. Unfortunately, the current supply chain management literature does not offer a definition for a dense area.

To evaluate the average internode distance and transfer it into the appropriate number of points on the scale from 1 to 5, a respective correlation is needed. Accordingly, “1” means a very low contribution to SCRES (very low-average internode distance). Contrastingly, “5” is very good regarding resilience, as denser supply chain networks are more vulnerable to disruptions. Table 1 shows the scorecard for this sub-factor.

For the sub-factor “number of dense areas within the supply chain,” a score of 5 means that no dense areas exist in the supply chain network, which increases resilience. Conversely “1” stands for many dense areas that affect SCRES negatively (see Table 2).

The problems with these two sub-factors are evident. Firstly, it lacks a definition for a “dense area” from a SCM perspective. Some parts of a supply chain are denser than others, but specific characteristics are missing. Secondly, even though average internode distance and number of dense areas can be calculated in a quantitative manner, indicators for each of the two sub-factors are not sufficient to establish what

**Table 1** Scorecard for internode distance

Score	Internode distance
1	Very low-average internode distance
2	Low-average internode distance
3	Moderate internode distance
4	High internode distance
5	Very high internode distance

**Table 2** Scorecard for number of dense areas

Score	Number of dense areas
1	Many dense areas exist within the supply chain
2	Several dense areas exist within the supply chain
3	Few dense areas exist within the supply chain
4	One dense area exists within the supply chain
5	No dense areas exist within the supply chain

is, or is not, resilient. Hence, the scorecards do not give exact figures for the distance and the number of dense areas.

#### 4.1.2 Node Criticality (Number of Critical Nodes, Number of Critical Paths)

The more important node or the path between two nodes is more critical for the resilience of the supply chain. Such critical nodes and paths decrease SCRES directly (Blackhurst et al. 2005; Craighead et al. 2007). To quantify this, distinct sub-factor traits are essential. Following Christopher and Peck (2004), the four characteristics of critical paths can be used to count the number of critical connections between nodes and nodes themselves.

The absolute number of both critical nodes and paths is not very insightful, as it strongly depends on the size of the considered supply network. For instance, the same number of critical nodes can be good for a long supply chain while indicating low resilience in a smaller network. The number of critical paths  $n_{pc}$  can be put in relation to all paths, which equal all pairs of nodes  $n_p$ , and critical nodes  $n_c$  in relation to the total number of nodes  $n$ . Correspondingly, the percentage share of critical paths  $cp\%$  and the percentage share of critical nodes  $cn\%$  are calculated as follows:

$$cp\% = \frac{n_{pc}}{n_p} \times 100; \quad cn\% = \frac{n_c}{n} \times 100$$

In line with this,  $cp\%$  and  $cn\%$  can be used as measures for the sub-factor node and path criticalities. High percentage shares of critical paths and nodes imply more potential vulnerabilities in a supply chain, and consequently lower resilience, as illustrated in Tables 3 and 4.

As with the first two sub-factors, “number of critical nodes” and “number of critical paths” can be calculated in a simple way. Determining the percentage share of critical nodes/paths that relates to the lowest resilience score is the main challenge. In fact, the assessment of both sub-factors based on the estimation that  $cp/n\% \geq 15\%$  is rated as the lowest contribution to SCRES.

**Table 3** Scorecard for critical nodes

Score	cn%
1	cn% $\geq$ 15%
2	15% > cn% $\geq$ 10%
3	10% > cn% $\geq$ 5%
4	5% > cn% $\geq$ 0%
5	0%

**Table 4** Scorecard for critical paths

Score	cp%
1	cp% $\geq$ 15%
2	15% > cp% $\geq$ 10%
3	10% > cp% $\geq$ 5%
4	5% > cp% $\geq$ 0%
5	0%

### 4.1.3 Supply Chain Complexity

Within the scope of this paper, supply chain complexity is only considered from a design perspective. Serdar-Asan (2013) distinguishes between three different types of supply chain complexity: static, dynamic, and decision-making. Interestingly, complexity concerning the supply chain structure is of a static nature. Dynamic complexity involves uncertainty, and decision-making combines both types. Craighead et al. (2007) suggest that supply chain complexity can simply be measured by summing up the total number of nodes and flows.

On first sight, it seems difficult to assess supply chain complexity accurately in this way, in the case of just one contemplated supply chain. However, this works well when comparing two similar large supply chains in order to determine which one is more complex. Still, this relatively simple way is a useful approach for measuring the sub-factor supply chain complexity. Naturally, larger supply networks would have more nodes and flows, which in fact makes them less resilient. Thus, following Craighead et al., complexity,  $c$ , is the sum of all nodes,  $n$ , and all flows, which are categorized into forward flows  $f_{forward}$ , backward flows  $f_{backward}$ , and within-tier flows  $f_{within-tier}$ .

$$c = n + f_{forward} + f_{backward} + f_{within-tier}$$

Consequently, the result for  $c$  indicates how resilient a company's supply chain is in terms of its network structure. According to this, firms with smaller breadth supply chains would have a higher score for this sub-factor, by default. This is actually correct, because small supply chains with less nodes and flows are less likely to be affected by a disruption. Table 5 shows the scores for the respective number of nodes and flows.

**Table 5** Scorecard for supply chain complexity

Score	c
1	$c \geq 500$
2	$500 > c \geq 350$
3	$350 > c \geq 250$
4	$250 > c \geq 150$
5	$c < 150$

**Table 6** Criteria for resilient suppliers

Criteria	Description
Catastrophic risk exposure	Applies when the probability of natural hazards is low and not likely to affect the supplier's site
Audit of risk profile	Applies when the supplier audits its own risk profile regularly
Monitoring and mitigation of risks	Applies when the supplier monitors and mitigates risks regularly
Supply chain continuity management	Applies when the supplier has established a supply chain continuity management system

## 4.2 Supplier-Related Factors

Supplier-related factors are part of the interorganizational category of SCRES elements. They include supplier selection, multiple sourcing, and flexibility in sourcing.

### 4.2.1 Supplier Selection

Risk-related factors are the key criteria in a resilience context with regard to supplier selection (Christopher and Peck 2004). General risk factors of a supply chain location can be the geographical location, political stability, or the economic position (Chen et al. 2014). Mitigation of such risks is the aim of SCRM rather than SCRES. In terms of resilience, unexpected disasters are of bigger importance. Thus, the “catastrophic risk exposure” (Knemeyer et al. 2009), which depends on the geographical location, is the first of four criteria. Consequently, it needs to be evaluated if the site of the vendor is exposed to catastrophic risks like earthquakes or floods. The remaining three factors concern the risk awareness of the supplier. Christopher and Peck (2004) propose “audit of own supply chain risk profile” and “procedures for monitoring and mitigation of risks” as the main criteria. Adding “supply chain continuity management,” which is crucial for resilient supplier selection according to Rajesh and Ravi (2015), four criteria are identified (see Table 6).

A resilient supplier selection requires all of these criteria. This means that if a particular supplier does not meet all four criteria, that firm should not be selected as a supplier. The score for this sub-factor depends on how many of the criteria are

**Table 7** Scorecard for supplier selection

Score	Number of positive criteria
1	0 criteria positive
2	1 criterion positive
3	2 criteria positive
4	3 criteria positive
5	4 criteria positive

utilized in the supplier selection process of the considered firm. Correspondingly, if none is taken into account, it means a score of 1, and if all are used, then the score is 5. Thus, the assessment of the sub-factor “supplier selection” is based on relevant selection criteria with regard to resilience. The score does not depend on how many of the suppliers fulfill the respective criteria. As a matter of fact, a resilient supplier should fulfill all of the identified characteristics. The selection criteria of the considered company are the determining variable, although in the current state of research there are no quantitative measures for the identified criteria (Table 7).

**4.2.2 Multiple Sourcing**

There are various ways of measuring the sub-factor “multiple sourcing.” Despite cost and quality disadvantages, having more than one supplier for a specific component will always reduce the effect of a supply chain disruption, at least to a small extent. Still, it is not clear that the more sources a firm uses, the more resilient it is with its sourcing strategy. For example, one could take the total number of suppliers in relation to the quantity of components in order to determine the resilience degree of a company. This could be an indicator, but it does not reveal anything about the allocation of suppliers of the various components. Another way of assessing a company’s degree of “multiple sourcing” is to count how many components are being procured through more than one supplier. The number of suppliers for each component is not taken into account, meaning that having five different suppliers for an individual part has the same influence on the score as having just two. Nonetheless, this simple calculation provides a lot of information about this particular sub-factor. Consequently, the percentage share  $ms\%$  of parts that are obtained by multiple sourcing is calculated by dividing all components that are, or at least could be, procured through more than one vendor  $p_{multiple\ sources}$  by all components  $p$ .

$$ms\% = \frac{p_{multiple\ sources}}{p} \times 100$$

Following this, a percentage share of 100% means the highest degree of resilience and five points according to the scorecard. In contrast, 0% corresponds to one point (see Table 8). The numbers for each score follow a consistent segmentation of the percentage share.

**Table 8** Scorecard for multiple sourcing

Score	$ms_{\%}$
1	$ms_{\%} < 20\%$
2	$40\% > ms_{\%} \geq 20\%$
3	$60\% > ms_{\%} \geq 40\%$
4	$80\% > ms_{\%} \geq 60\%$
5	$100\% > ms_{\%} \geq 80\%$

### 4.2.3 Flexibility in Sourcing

Although many authors in the field of supply chain resilience see multiple sourcing and sourcing flexibility as the same thing, like Pereira et al. (2014), these sub-factors are treated separately in the scope of this paper. According to Petit et al., multiple suppliers are part of “flexibility in sourcing.” Thus, using multiple vendors enables flexibility. Even so, sourcing flexibility has many aspects that play a role in terms of SCRES. Petit et al. (2013) define six different sub-factors for “flexibility in sourcing,” which is one of their fourteen capability factors: part commonality, modular product design, multiple uses, supplier contract flexibility, multiple sources.

These sub-factors are conceivable to assess a supply chain’s capability of “sourcing flexibility.” It would include determining how many of the identified flexibility factors are used by the contemplated firm. The more strategies that are implemented, the higher the respective score. Transferred to the scorecard, the implementation of all six flexibility strategies equals five points. As five factors are taken into account, one or zero used techniques mean zero points (see Table 9).

The obvious difficulty is that the awarding of scores is still based on qualitative evaluations. It needs to be decided if, for example, part commonality or modular product design is given in the object of study. Clear definitions are needed in order to determine if a company makes use of a specific strategy or not. As far as multiple sourcing is concerned, the percentage share of multiple sourcing  $ms_{\%}$  can be used as an indicator, defining that starting from a specific share, for instance  $ms_{\%} = 75\%$ , this sub-factor is “positive.” Similar measures or indicators are necessary for the other sub-factors as well.

The second problem concerns mainly modular product design. The implementation of this strategy depends on the characteristics of the outcome. Despite its

**Table 9** Scorecard for flexibility in sourcing

Score	Description
1	0 or 1 strategy
2	2 strategies
3	3 strategies
4	4 strategies
5	5 strategies

**Table 10** Measures for connectivity and willingness (Allred et al. 2009)

Measures for connectivity	Measures for willingness
Integration of information applications in the firm and the supply chain	Willingness to share information among supply chain members
Existence of information system linkages with suppliers and customers	
	Frequency of information sharing among supply chain members
	Existence of senior-level managerial interaction among supply chain members

advantages, modular product design is not always suggestive or even possible. In that case, it cannot be considered for the assessment of “flexibility in sourcing.”

### 4.3 Relational Competencies

The factor of relational competencies consists of three sub-factors: information sharing, collaboration, and contingency planning. The central aspects of information sharing are the two proposed dimensions of connectivity and willingness. In fact, one does not work without the other. If a company has sufficient information sharing systems and technology but is not willing to make use of them, the contribution to resilience is low and vice versa. Firms that want to communicate with suppliers and customers but lack the necessary infrastructure do not have a high level of information sharing.

Hence, a measurement tool for information sharing does not exist, but it is possible to assess the extent of information sharing in a particular firm or supply chain. The following approach to assess the sub-factor of relational competencies is based on different levels of communication. Altogether, five measures for the dimensions of connectivity and willingness are adopted from Allred et al. (2009).

According to the five-point rating scale, five levels of information sharing determine the contribution to SCRES, which are characterized by the measures in Table 10. As explained, willingness alone cannot enable communication in supply chains. Information applications and systems are inalienable requirements. While the score 1 is the absence of these measures, the score 5 includes an appropriate implementation of all measures (see Table 11).

#### 4.3.1 Collaboration

The coherence between information sharing and collaboration is not clearly established. Although definitions of supply chain collaboration are not consistent, the

**Table 11** Scorecard for information sharing

Score	Description
1	(1) No information applications are integrated into the firm and the supply chain, and (2) no information system linkages exist with suppliers and customers
2	(1) Information applications are integrated into the firm and the supply chain, and (2) information system linkages exist with suppliers and customers but (3) low willingness to share information among supply chain members
3	(1) Information applications are integrated into the firm and the supply chain, and (2) information system linkages exist with suppliers and customers as well as (4) occasional information sharing among supply chain members
4	(1) Information applications are integrated into the firm and the supply chain, and (2) information system linkages exist with suppliers and customers as well as (4) frequent open information sharing among supply chain members
5	(1) Information applications are integrated into the firm and the supply chain, and (2) information system linkages exist with suppliers and customers as well as (4) frequent open information sharing and (5) senior-level managerial interaction among supply chain members

aim is unambiguous: Collaboration is supposed to lead to transparency and visibility (Holweg et al. 2005).

There are several collaboration initiatives such as vendor-managed inventory (VMI), efficient consumer response (ECR), collaborative planning, forecasting, and replenishment (CPFR), and continuous replenishment (CR) (Ireland and Crum 2005). A possible approach to assessing a company's collaboration capability could be to gather the most common initiatives in order to detect how many of them are implemented, similar to the assessment of "flexibility in sourcing." The more identified initiatives that are used, the higher the visibility, thus a higher score and more resilience.

Holweg et al. (2005) distinguish between four different types of supply chains by means of collaboration. Planning collaboration and inventory collaboration are the crucial dimensions. The first type is referred to as the "traditional supply chain," which means that neither upstream nor downstream tiers collaborate. It is followed by the "information exchange" supply chain. Retailer and supplier exchange demand information as well as action plans and thus align their forecasts. In the "vendor-managed replenishment" supply chain, the supplier is responsible for managing the customer's inventory. Finally, in the last type, the supply is synchronized, which means that the supplier takes replenishment into account for his own production and material planning.

In order to use this classification as the foundation for the assessment of the sub-factor "collaboration," a fifth supply chain level needs to be added: The "pre-collaborative supply chain" is between the first and second type. No information is shared in the "traditional supply chain," and information is actively exchanged in the "information exchange supply chain." Thus, the "pre-collaborative supply chain" is characterized by a state where the issue of collaboration is understood and first efforts to collaborate were undertaken. However, unlike the second type, according



**Table 12** Scorecard for collaboration

Score	Description
1	“Traditional supply chain”—with no collaboration
2	“Pre-collaborative supply chain”—no collaboration structures established yet
3	“Information exchange supply chain”—alignment of forecasts
4	“Vendor-managed replenishment”—supplier responsible for customer’s inventory
5	“Synchronized supply chain”—supplier’s production and material planning are aligned with replenishment

**Table 13** Scorecard for contingency planning

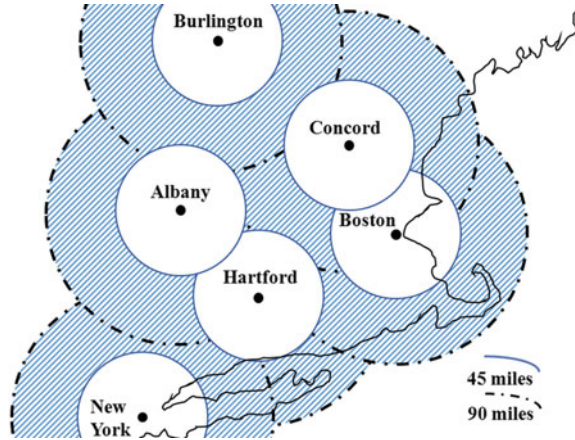
Score	Description
1	No contingency plans
2	Contingency plans exist for single functional areas
3	Contingency plans exist for single sites
4	Customer and supplier are integrated into contingency plans
5	The entire supply chain is integrated into contingency plans

to Holweg et al. (2005), adequate structures and technology are not established yet. Table 12 shows the scorecard for this sub-factor with the four adopted and one added “collaboration levels.”

### 4.3.2 Contingency Planning

Contingency planning is one way of increasing resilience. With the fast-changing business environment and many new risks, organizations are forced to develop plans that facilitate a fast response to disruptions. The cornerstone of contingency planning does not concern the mere existence of such plans. Skipper and Hanna (2009) state contingency planning is not yet a multi-organizational function, as it is often implemented around single functional areas only. It can be concluded that contingency plans, which are integrated on a supply chain network level instead of single departments, are more conducive to SCRES. This is a starting point for the assessment of the sub-factor “contingency planning.” Thus, the integration level of contingency planning, from no plans at all to contingency plans that include all parts of a supply chain, determines the capability score regarding this sub-factor as shown in Table 13.

**Fig. 3** Areas for the location of secure backup facilities based on Ratick et al. (2008, p. 648)



### 4.4 Physical Capital Resources

#### 4.4.1 Backup Facilities

Day-to-day operational costs and costs of expected failure, as well as probability of an event occurrence, are decisive for the number and location of such facilities. Sites that are physically too close together can be affected by the same disaster, which causes a disruption, but if they are located too far apart, operations can become economically infeasible (Ratick et al. 2008). Following this basic principle, Hale and Moberg (2005) discuss the optimal location for backup facilities. The objective is the “selection of a minimum number of emergency resource locations that provide logistics managers with quick access to critical resources while minimizing the total costs spent by the supply chain preparing for future crises” (Hale and Moberg 2005). Hence, they developed a four-step secure site decision process.

In order to measure the sub-factor “backup facilities,” the approach of Hale and Moberg (2005) can be utilized. Each supply chain facility needs to have at least one backup site that contributes to a fast recovery after a disruption. These backup sites should be within a specified “cover” distance,  $C$ . As locations that are too close to each other can be subject to the same hazard, the “anticover” distance,  $A$ , is the second requirement for a safe backup facility (see Fig. 3) (Ratick et al. 2008). The scorecard for this sub-factor is based on the assumption that, in terms of backup facilities, a supply chain can be said to be resilient if each supply chain facility has at least one backup site within a distance according to the model of Hale and Moberg (2005). This is done by calculating the percentage share of facilities  $bf\%$  that meet this requirement. In order to do so, the number of supply chain facilities with an adequate backup site  $scf_{backup}$  needs to be divided by all supply chain facilities,  $scf$ .

$$bf\% = \frac{scf_{backup}}{scf}$$

**Table 14** Scorecard for backup facilities

Score	Description
1	$bf_{\%} < 20\%$
2	$40\% > bf_{\%} \geq 20\%$
3	$60\% > bf_{\%} \geq 40\%$
4	$80\% > bf_{\%} \geq 60\%$
5	$100\% > bf_{\%} \geq 80\%$

**Table 15** Resilience enabling technologies based on Blackhurst et al. (2005), Prajogo and Olhager (2012)

Resilience enabling supply chain technologies
Exception reporting systems and predictive tools for early awareness of impending disruptions
Risk monitoring systems for each node of the supply chain
Tools for quickly redesigning the supply chain
Information systems to track/locate resources

The correlation according to the five-point rating scale (see Table 14) is similar to the one of the sub-factor “multiple sourcing.”

The problem is that “cover” distance,  $C$ , and “anticover” distance,  $A$ , are not generally defined. Not every area of a supply chain is threatened by hazards to the same extent. Therefore, different regions and parts of a supply chain network need to be considered and assessed separately concerning the distances.

#### 4.4.2 Technology

The sub-factor “technology” cannot be measured quantitatively. However, similar to “flexibility in sourcing,” it can be assessed. The basis for this is the three technologies/tools identified by Blackhurst et al. (2005), shown in Table 15, and additionally a technology adopted from Prajogo and Olhager, which is “information systems to track/locate resources” (Prajogo and Olhager 2012). The four suggested technologies cover all the relevant domains that require increased visibility that are discussed as part of the sub-factors “information sharing” and “collaboration,” apart from relational competencies. Remaining issues concern technologies that enhance predictability, monitoring, and redesigning the supply chain. The more technologies that are implemented by a firm/supply chain, the higher the resilience score is for this sub-factor (see Table 16).

#### 4.4.3 Safety Stock

Despite the disadvantages, carrying safety stock is one of the most common strategies to buffer against supply risks (Giunipero and Eltantawy 2004). Yet, although it is

**Table 16** Scorecard for technology

Score	Description
1	0 technologies implemented
2	1 technology implemented
3	2 technologies implemented
4	3 technologies implemented
5	4 technologies implemented

part of most of the resilience frameworks, none of the researchers analyze the precise extent of safety stock that is needed. Mostly, authors only refer to the mere presence of safety stock as an enabler of SCRES (Blackhurst et al. 2005; Giunipero and Eltantawy 2004; Hoheinstein et al. 2015). In line with this, the scorecard for the sub-factor “safety stock” in principle resembles the measurement of backup facilities. In fact, the particular degree of safety stock is not considered. Thonemann and Klein (2011) suggested five different maturity levels for inventory in supply chains. The scorecard for this sub-factor based on the inventory maturity level is shown in Table 17.

### 4.5 Human Capital Resources

Leadership, multi-disciplinary teams, and understanding of risk are identified as the core elements of SCRES regarding human capital resources. In order to measure these three sub-factors individually, a very detailed analysis is necessary. More than the other considered factors, human capital resources need to be viewed from a management perspective. A quantitative measurement seems impossible, as precise indicators or different levels have to be defined for each sub-factor, although using qualitative references, “human capital resources” can be assessed. Considering “human capital resources” as only one factor, the three sub-factors can be seen as different levels of the degree of resilience. Leadership in a resilience context is useless if a risk management culture is not existent. Similarly, multi-disciplinary teams that work in

**Table 17** Scorecard for the sub-factor safety stock

Score	Inventory maturity level according to Thonemann and Klein (2011)
1	Same parameter is used to calculate the inventory target levels for all products
2	Individual stock parameters are applied, based on the planners’ experience
3	Individual stock parameters are applied to each product segment
4	Analytical optimization models for the determination of safety stock levels are applied—single-stage inventory optimization
5	Multistage approaches for the joint planning and optimization of inventory levels throughout the supply chain are applied

**Table 18** Scorecard for human capital resources

Score	Description
1	Risk management culture does not exist, and fundamental assumptions are not yet understood
2	Risk management culture exists but is not yet internalized by all employees
3	Risk management culture is internalized by all employees, and cost/benefit trade-offs when managing risk in supply chains are understood
4	Employees are educated and trained to execute supply chain contingency plans, and leaders are present
5	Cross-functional risk management teams are established

order to monitor risks and predict possible threats cannot function effectively if the employees involved lack of essential understanding of the issue.

To classify a company's resilience ability regarding human capital resources, at least five different levels need to be defined. "Education and training of employees to execute supply chain contingency plans" and "understanding of cost/benefit trade-offs when managing risk in supply chain" are two identified resilience enhancers in terms of human capital resources by Blackhurst et al. (2011). Adopting these two, the corresponding scorecard (Table 18) looks as follows.

#### 4.6 Overall Resilience Score

The respective scores of all the sub-factors contribute to the capability of a company or supply chain to be resilient. The overall resilience score  $R$  is calculated as follows:

$$R = \frac{C}{5}$$

The resilience capability  $C$  is calculated by averaging the five factor scores  $C_{1,2,3,4,5}$ :

$$C = \frac{\sum_{j=1}^{n_C} C_j}{n_C}, n_C = 5$$

The factor scores  $C_j$  are averaged from the respective sub-factors  $C_{j,k}$  (see Table 19):

$$C_j = \frac{\sum_{k=1}^{n_{c_j}} C_{j,k}}{n_{c_j}}, j = 1 \rightarrow n_C$$

Three different ways of determining the score for the sub-factors are used: Sub-factors that can be quantified have a scorecard with a ranking system according to the

**Table 19** Overview resilience factors and sub-factors

Resilience factors $C_j$	Sub-factors $C_{j,k}$
Supply chain design	(1) Average internode distance, (2) number of dense areas, (3) number of critical paths, (4) number of critical nodes, (5) supply chain complexity
Supplier-related factors	(1) Supplier selection, (2) multiple sourcing, (3) flexibility in sourcing
Relational competencies	(1) Information sharing, (2) collaboration, (3) contingency planning
Physical capital resources	(1) Backup facilities, (2) technology, (3) safety stock
Human capital resources	(1) Human capital resources

respective measure, for example “average internode distance.” For sub-factors that cannot be quantified, qualitative indicators are utilized. These can be certain characteristics that concern the related sub-factor, for example “human capital resources,” or different strategies or criteria, for instance “technology,” that help to determine the score. However, no matter how detailed and well described the qualitative indicators are, the assessment of several sub-factors remains subjective to a certain extent. “Information sharing” is a good example of that: Even though the scorecard says clearly which requirements correspond to which score, these still need to be evaluated. The correlation between the factors and sub-factors is not part of the measurement concept. All sub-factors are considered individually. This, and the assumption of equal weights for all factors, based on Petit et al. (2013), allows the calculation of the resilience score in a simple manner. In order to determine the weight for each factor and validate the developed concept, an empirical study is needed. Another main issue is to compare results between different resilience scores and quantify the quality of resilience index. Petit et al. (2013) suggest utilizing the five-point Likert to identify the resilience index and assume equal weights for each factor.

## 5 Conclusion and Future Research

As SCRES research is relatively novel and not well researched to date, the aim of this chapter is to develop a concept for assessing supply chain resilience. Compared to the high number of distinct resilience concepts, the proposed definitions differ slightly. A detailed analysis of the roots of resilience as well as its phases and formative elements is a vital process step in order to develop a concept for assessing SCRES. As demonstrated in this chapter, resilience is composed of many different competencies. Therefore, it is often considered a concept or strategy rather than a certain capability of a supply network. To summarize, the study revealed two main difficulties in the development of a concept for measuring SCRES. The first one relates to finding quantitative numbers or indices for the particular sub-factors. Unfortunately, this simply cannot be done for some factors, for example “relational competencies” or

“human capital resources.” However, specifically concerning supply chain design factors, appropriate measures can be calculated and implemented in the concept. If this is not possible, qualitative indicators need to be established.

The second issue concerns the correlation between known measures/indicators, quantitative or qualitative, and the respective resilience scores. Even if the quantitative measurement of a certain sub-factor is possible, there is no evidence for how it correlates with the five-point ranking scale. As research in this field is not yet sufficiently advanced, the corresponding scorecards are sometimes still based on subjective estimations. The same holds true for qualitative measures.

Another issue relating to the development of the concept concerns contradictions. This is clarified when considering, for example, the two sub-factors of “multiple sourcing” and “supply chain complexity.” Multiple sourcing is a resilience enabler, while supply chain complexity reduces resilience. However, each additional source adds a redundant path, which increases complexity. As a matter of fact, a supplementary supplier increases and diminishes resilience at the same time.

Companies need a structured, methodical, and incremental approach for implementing SCRES holistically. In the course of this, the enablers of resilience need to be considered as a whole. A well-defined procedure is necessary because the implementation of some elements is conditional to the existence of certain structures. This means that there might be a chronological order for building resilience, which needs to be explored in the future. Furthermore, supply chains have different characteristics due to the demands of different industries. These circumstances need to be taken into account for effective implementation.

The cost/benefit trade-off is vital and determines if actions that were taken to achieve resilience were advisable. Although often mentioned in the specialized literature, there is a lack of any detailed analysis. If investments in resilience are too low, the vulnerability of the supply chain is too high. At the same time, profits will erode if companies do not balance their efforts. This compromise between additional costs and use of resilience-related actions needs to be quantified in the future. Obviously, having a valid tool to measure SCRES in a quantitative way is a necessary requirement. Such a tool can be based on the concept for assessing supply chain resilience developed here and, in addition, integrate the importance and interrelations of resilience elements.

## References

- Allred, C., Wallin, C., Magnan, G., & Fawcett, S. E. (2009). Supply chain information-sharing: Benchmarking a proven path. *Benchmarking: An International Journal*, 19(2), 222–246.
- Asbjørnslett, B. (2008). Assessing the vulnerability of supply chains. In G. A. Zsidisin & B. Ritchie (Eds.), *Supply chain risk: A handbook of assessment, management and performance* (pp. 15–33). New York, NY: Springer.
- Blackhurst, J., Craighead, C. W., Elkins, D., & Handfield, R. B. (2005). An empirically derived agenda of critical research issues for managing supply-chain disruptions. *International Journal of Production Research*, 43(19), 4067–4081.

- Blackhurst, J., Dunn, K. S. & Craighead, C. W. (2011). An empirically derived framework of global supply resiliency. *Journal of business logistics*, 32(4), 374–391.
- Cardoso, S., Barbosa, A. P. F. D., Relvas, S., & Novais, A. (2014). Resilience assessment of supply chains under different types of disruption. In *Proceedings of the 8th International Conference on Foundations of Computer-Aided Process Design* (pp. 759–764).
- Cardoso, S., Barbosa, A. P. F. D., Relvas, S., & Novais, A. (2015). Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty. *Omega*, 56, 53–73.
- Carvalho, H., Barroso, A. P., Machado, V. H., Azevedo, S., & Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Computers & Industrial Engineering*, 62(1), 329–341.
- Chan, H., & Chan, F. (2010). Comparative study of adaptability and flexibility in distributed manufacturing supply chains. *Decision Support Systems*, 48(2), 331–341.
- Chen, A., Hsieh, C. Y., & Wee, H. M. (2014). A resilient global supplier selection strategy—A case study of an automotive company. *The International Journal of Advanced Manufacturing Technology*, 87(5–8), 1475–1490.
- Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management*, 15(2), 1–13.
- Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., & Handfield, R. B. (2007). The severity of supply chain disruptions: Design characteristics and mitigation capabilities. *Decision Sciences*, 38(1), 131–156.
- Falasca, M., Zobel, C. W., & Cook, D. (2008). A decision support framework to assess supply chain resilience. In *Proceedings of the 5th International ISCRAM Conference, Washington, DC, USA* (pp. 596–605).
- Fiksel, J., Polyviou, M., Croxton, K. L., & Petit, T. J. (2015). From risk to resilience—Learning to deal with disruption. *MIT Sloan Management Review*, 56(2), 79–86.
- Giunipero, L. C., & Eltantawy, R. A. (2004). Securing the upstream supply chain: A risk management approach. *International Journal of Physical Distribution & Logistics Management*, 34(9), 698–713.
- Güller, M., et al. (2015). A simulation-based analysis of supply chain resilience. In W. Kersten, T. Blecker, & C. Ringle (Eds.), *Innovative methods in logistics and supply chain management* (pp. 533–557). Berlin: epubli GmbH.
- Hale, T., & Moberg, C. R. (2005). Improving supply chain disaster preparedness: A decision process for secure site location. *International Journal of Physical Distribution & Logistics Management*, 35(3), 195–207.
- Hoheinstein, N. O., Feisel, E., Hartmann, E., & Giunipero, L. (2015). Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation. *International Journal of Physical Distribution & Logistics*, 45(1–2), 90–117.
- Holweg, M., Disney, S., Holmström, J., & Smaros, J. (2005). Supply chain collaboration: Making sense of the strategy continuum. *European Management Journal*, 23(2), 170–181.
- Hongler, M., et al. (2010). Centralized versus decentralized control—A solvable stylized model in transportation. *Physica A*, 389(19), 4162–4171.
- Ireland, R. K., & Crum, C. (2005). *Supply chain collaboration. How to implement CPFR and other best collaborative practices*. Boca Raton: J. Ross Publishing.
- Jüttner, U. (2005). Supply chain risk management: Understanding the business requirements from a practitioner perspective. *The International Journal of Logistics Management*, 16(1), 120–141.
- Kamalahmadi, M., & Parast, M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics*, 171(1), 116–133.
- Kleindorfer, P., & Saad, G. (2005). Managing disruption risks in supply chains. *Production and Operations Management*, 14(1), 53–68.
- Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. *European Journal of Operations Research*, 203(2), 283–293.



- Knemeyer, A. M., Zinn, W., & Eroglu, C. (2009). Proactive planning for catastrophic events in supply chains. *Journal of Operations Management*, 27(2), 141–153.
- Longo, F., & Ören, T. (2008). *Supply chain vulnerability and resilience: A state of the art overview*. Italy: Campora S. Giovanni.
- Lotfi, M., Sodhi, M., & Kocabasoglu-Hillmer, C. (2013). *How efforts to achieve resiliency fit with lean and agile practices*. USA: Denver.
- Mandal, S. (2012). An empirical investigation into supply chain resilience. *Journal of Supply Chain Management*, 9(4), 46–61.
- Manuj, I., & Mentzer, J. T. (2008). Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management*, 38(3), 192–223.
- Melnyk, S. A., et al. (2014). Understanding supply chain resilience. *Supply Chain Management Review*, 18(1), 35–41.
- Nair, A., Narasimhan, R., & Choi, T. (2009). Supply networks as a complex adaptive system: Toward simulation-based theory building on evolutionary decision making. *Decision Sciences*, 40(4), 783–815.
- Pereira, C. R., Christopher, M., & Da Silva, A. L. (2014). Achieving supply chain resilience: The role of procurement. *Supply Chain Management: An International Journal*, 19(5–6), 626–642.
- Petit, F., et al. (2012). Developing an index to assess the resilience of critical infrastructure. *International Journal of Risk Assessment and Management*, 16(1), 28–47.
- Petit, T. J., Fiksel, J., & Croxton, K. L. (2013). Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics*, 31(1), 1–21.
- Ponomarev, S., & Holcomb, M. (2009). Understanding the concept of supply chain resilience. *International Journal of Logistics Management*, 20(1), 124–143.
- Prajogo, D., & Ohlager, J. (2012). Supply chain integration and performance: The effects of long term relationships, information technology and sharing, and logistics integration. *International Journal of Production Economics*, 135(1), 514–522.
- Rajesh, R., & Ravi, V. (2015). Supplier selection in resilient supply chains: A grey relational analysis approach. *Journal of Cleaner Production*, 86(1), 343–359.
- Ratick, S., Meacham, B., & Aoyama, Y. (2008). Locating backup facilities to enhance supply chain disaster resilience. *Growth and Change*, 39(4), 642–666.
- Rice, J. B., & Caniato, F. (2003). Building a secure and resilient supply network. *Supply Chain Management Review*, 7(5), 22–30.
- Scholten, K., Sharkey, S. P., & Fynes, B. (2014). Mitigation processes—Antecedents for building supply chain resilience. *Supply Chain Management: An International Journal*, 19(2), 211–228.
- Schmitt, A. J., & Singh, M. (2012). A quantitative analysis of disruption risk in a multiechelon supply chain. *International Journal of Production Economics*, 139(1), 22–32.
- Serdar-Asan, S. (2013). A review of supply chain complexity drivers. *Computers & Industrial Engineering*, 66(3), 533–540.
- Sheffi, Y. (2004). Demand variability and supply chain flexibility. In G. Prockl, A. Bauer, A. Pflaum, & U. Müller-Steinfahrt (Eds.), *Entwicklungspfade und Meilensteine moderner Logistik* (pp. 85–117). Wiesbaden: Gabler Verlag.
- Skipper, J. B., & Hanna, J. B. (2009). Minimizing supply chain disruption risk through enhanced flexibility. *International Journal of Physical Distribution & Logistics Management*, 39(5), 404–427.
- Snell, P. (2010). Beware of the risks, and snap up the opportunities in 2010. In *IFPSM ezine Highlights*. Retrieved from <http://www.ifpsm-ezine.org/S>.
- Soni, U., Jain, V., & Kumar, S. (2014). Measuring supply chain resilience using a deterministic modeling approach. *Computers & Industrial Engineering*, 74(2014), 11–25.
- Spiegler, V., Naim, M., & Wikner, J. (2012). A control engineering approach to the assessment of supply chain resilience. *International Journal of Production Research*, 50(21), 6162–6187.
- Swafford, P., Ghosh, S., & Murthy, N. (2006). The antecedents of supply chain agility of a firm: Scale development and model testing. *Journal of Operations Management*, 24(2), 170–188.
- Tang, C., & Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics*, 116(1), 12–27.

- Thonemann, U. W., & Klein, M. (2011). Benefits of multi-stage inventory planning in process industries. 28. *Deutscher Logistik Kongress*, 19.–21. October, Berlin.
- Tomlin, B., & Synder, L. (2008). *On the value of a threat advisory system for managing*, s.l.: s.n.
- Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: A relational view. *International Journal of Physical Distribution & Logistics Management*, 43(4), 300–320.
- Zsidisin, G. A. (2003). Managerial perceptions of supply risk. *The Journal of Supply Chain Management*, 39(1), 14–26.