Int. J. Production Economics 126 (2010) 121–129

Contents lists available at ScienceDirect

Int. J. Production Economics

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

Assessing the vulnerability of supply chains using graph theory

Stephan M. Wagner *, Nikrouz Neshat

Chair of Logistics Management, Department of Management, Technology, and Economics, Swiss Federal Institute of Technology Zurich, Scheuchzerstrasse 7, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 15 January 2009
Accepted 6 October 2009
Available online 27 October 2009

Keywords:
Supply chain management
Risk management
Vulnerability
Graph theory
Measurement
Large-scale survey

ABSTRACT

In today's business environment, harsher and more frequent natural and man-made disasters make supply chains more vulnerable. Supply chain disruptions now seem to occur more frequently and with more serious consequences. During and after supply chain disruptions, companies may lose revenue and incur high recovery costs. If supply chain managers were more capable of measuring and managing supply chain vulnerability, they could reduce the number of disruptions and their impact. In this research we developed an approach based on graph theory to quantify and hence mitigate supply chain vulnerability. Quantification of supply chain vulnerability aids managers in assessing the vulnerability of their supply chains (e.g., across and between supply chains, or over time) and in comparing the effectiveness of different risk mitigation strategies.

1. Introduction

As a result of changes in the economic, business and ecological environments, modern supply chains seem to be more vulnerable than ever before, for several reasons. First, disasters have increased in number and in intensity during the last decades. Natural disasters such as droughts, floods, windstorms, hurricanes, earthquakes or tsunamis strike more often and have a greater economic impact (e.g., Munich Re, 2006). At the same time, the number of man-made disasters such as accidents, wars, terrorist attacks, strikes, or sabotage that affect supply chains has increased (e.g., Colema, 2006). The Centre for Research on the Epidemiology of Disasters (2004) has observed that disasters have increased exponentially worldwide over the past decades (Fig. 1). There is general agreement that global supply chains are suffering from the disruption of supply chain functions and reduced supply chain efficiencies (e.g., Bogataj and Bogataj, 2007; Myers et al., 2006; Tang, 2006a).

Second, today's supply chains are more complex than they used to be. There are various reasons for supply chain complexity, such as higher levels of R&D and manufacturing outsourcing, supplier–supplier relationships in supplier networks, increased dependence on supplier capabilities, new technologies (e.g., Internet, RFID), regulatory requirements (e.g., post 9/11 security regulations such as C-TPAT, or food safety controls), shorter product life-cycles due to rapidly changing customer preferences, and international market and production expansion.

Third, supply chain executives have strived to improve their financial performance, which is measured with ratios such as return on assets (ROA). They have implemented numerous supply chain initiatives to boost revenues (e.g., increased product variety, frequent rollouts of new products), cut costs (e.g., reduced supply base, just-in-time inventory system, vendor-managed inventory) and reduce assets (e.g., outsourced manufacturing) (Craighead et al., 2007; Tang, 2006a; Wagner and Bode, 2006; Zsidisin et al., 2005). Although such efficiency-driven supply chain management measures have immense potential to make operations leaner and more efficient in a stable environment, they also make them more prone to disruptions (Hauser, 2003). All these attempts to drive cost out of supply chains have left fewer buffers; hence there is less margin of error for supply chains and should a major disruption occur, it comes at a stratospheric cost (Lee, 2004).

Fourth, with competition becoming fiercer, competitive pressures often force companies to assume more "calculated risks" (Svensson, 2002)—risks that managers must accept in order to improve competitiveness, reduce costs and improve profitability. However, the downside potential of the "calculated risks" could have adverse consequences that jeopardize the whole supply chain's ability to serve the final customers, thus affecting firms' long-term goal accomplishment (Svensson, 2002).

The widespread disruptions cited in the literature (e.g., Chopra and Sodhi, 2004; Martha and Subbakrishna, 2002; Sheffi, 2005), underline that vulnerability of modern supply chains can subsequently result in supply chain disruptions and detrimental effects for firms (Hendricks and Singhal, 2005; Wagner and Bode, 2008).

Despite these obvious reasons for higher supply chain vulnerability and its impact on firm performance, the understanding of the supply chain vulnerability concept still remains on a conceptual and normative level (e.g., Jüttner et al., 2003; Peck, 2005; Svensson, 2004). While supply chain vulnerability is starting to receive some empirical support (e.g., Wagner and Bode, 2006), supply chain managers still need to be better

* Corresponding author. Tel.: +41 44 632 3259; fax: +41 44 632 1526.
E-mail address: stwagner@ethz.ch (S.M. Wagner).

0925-5273/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpe.2009.10.007

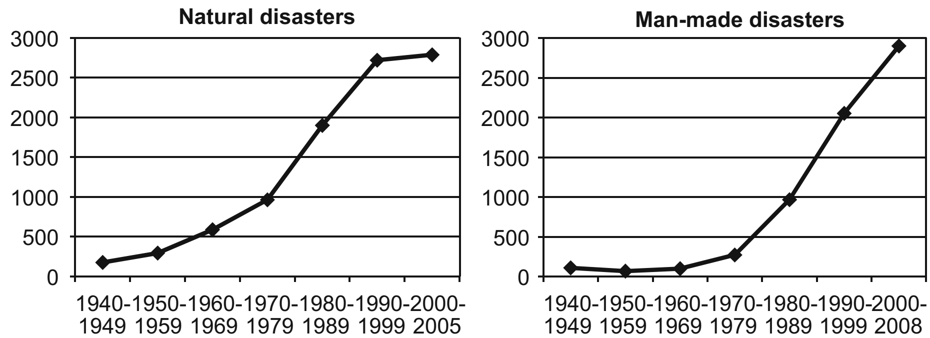


Fig. 1. Distribution of natural and man-made over time. (*Source*: Centre for Research on the Epidemiology of Disasters, 2004.)

equipped with methods of measuring and managing supply chain vulnerability. In line with the frequently cited business wisdom "You can't manage, what you don't measure" supply chain managers need support in quantifying and thus mitigating supply chain vulnerability. They somehow need to calculate the supply chain risk exposure of a firm and as a consequence determine the effectiveness of supply chain risk management measures. Firms may find it difficult to justify certain costly strategies for mitigating supply chain disruptions that rarely occur. With respect to supply chain management, Chen and Paulraj (2004, p. 136) argue that "the scientific development of a coherent supply chain management discipline requires that advances be made in the development of measurement instruments". Along these lines, supply chain vulnerability also has to be measured and quantified (Kleindorfer and Saad, 2005). Measurement of supply chain vulnerability is by and large regarded as difficult because it is multi-dimensional and there are no well-developed metrics for evaluating the factors on which vulnerability depends (Wagner and Bode, 2006).

Given this deficiency, the main objectives of this research are to develop a quantitative approach using graph modeling to measure vulnerability using its drivers and their interdependencies, and to demonstrate how the resulting supply chain vulnerability index (SCVI) can be applied to real-world data.

The remainder of the article is organized as follows. Section 2 begins with a review of the theoretical foundations of supply chain vulnerability and its drivers. In Section 3, the graph modeling is explained. Empirical data is used to illustrate the application of the supply chain vulnerability index in Section 4. The graph modeling approach and the results of the empirical analysis are discussed in Section 5. The article concludes in Section 6 with limitations and recommendations for future research.

2. Supply chain vulnerability and its drivers

2.1. Conceptual framework for supply chain risk management

Because supply chain disruptions can have long-term negative effects on a firm's financial performance (Hendricks and Singhal, 2003, 2005) it is widely accepted that supply chain risk management (SCRM) is a necessity in today's business. Among others, Christopher and Lee (2004) or Tang (2006a) recognize the increasing risks in the supply chain context and the need to manage them. Fig. 2 depicts the relationship between supply chain disruption and supply chain vulnerability. The failure to understand the potential vulnerabilities can compromise the supply chain's ability to handle supply chain disruptions. As a result, vulnerability should be managed by implementing various SCRM approaches. Jüttner et al. (2003) proposed in their agenda for future research in SCRM that new approaches have to be developed to assist managers to track the vulnerabilities of their supply chains. By understanding and managing these vulnerabilities, an organization can more clearly identify its options for SCRM (i.e., which SCRM approaches are appropriate in a given situation). Companies no longer retain their competitive advantage without a proactive SCRM approach to their vulnerabilities.

2.2. Supply chain vulnerability

Supply chain vulnerability has been defined broadly by Christopher and Peck (2004, p. 3) as "an exposure to serious disturbance" and by Jüttner et al. (2003, p. 200) as "the propensity of risk sources and risk drivers to outweigh risk mitigating strategies, thus causing adverse supply chain consequences". Wagner and Bode (2006, p. 304) state that "supply chain vulnerability is a function of certain supply chain characteristics and that the loss a firm incurs is a result of its supply chain vulnerability to a given supply chain disruption". Since then, Wagner and Bode (2009, p. 278) defined the concept of vulnerability in a supply chains context more precisely:

> While a supply chain disruption is the trigger that leads to the occurrence of risk, it is not the sole determinant of the final loss. It seems consequential that also the susceptibility of the supply chain to the harm of this situation is of significant relevance. This leads to the concept of supply chain vulnerability. The basic premise is that supply chain characteristics are antecedents of supply chain vulnerability and impact both the probability of occurrence as well as the severity of supply chain disruptions.

For the purpose of this article, we adopt this latter definition. As a consequence, if supply chain managers can alleviate these supply chain characteristics, they can reduce its vulnerability and the detrimental effects for the focal firm and the supply chain as a whole.

2.3. Supply chain vulnerability drivers

According to the definitions, supply chain vulnerability is the result of certain "drivers" (supply chain characteristics or antecedents). The vulnerability of a supply chain itself cannot be observed, but the variables that determine the level of vulnerability.

Extending the more general reasons for increased vulnerability of supply chains discussed in Section 1, we categorize supply chain vulnerability drivers (SCVD) into three groups: supply side, demand side, and supply chain structure vulnerabilities.

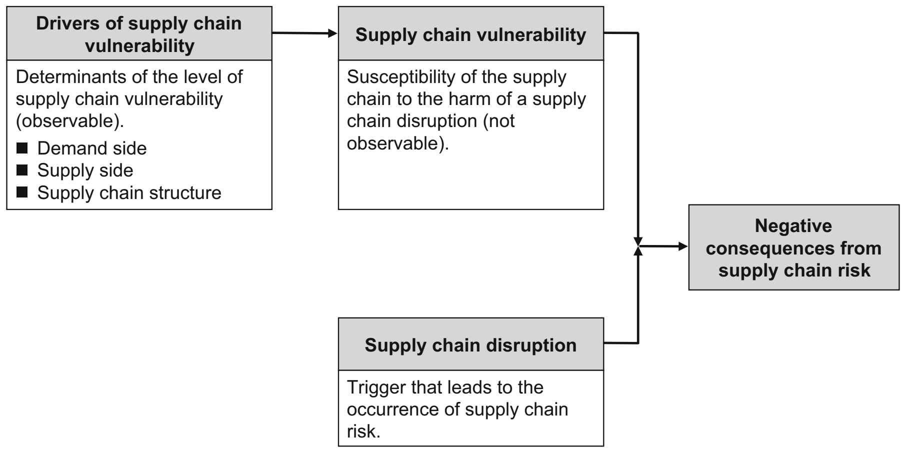


Fig. 2. Supply chain vulnerability and disruption.

Vulnerability drivers on the *demand side* reside in the downstream supply chain operation. This includes the customer (e.g., customer dependence, financial situation of the customer), the product and its characteristics (e.g., its complexity and life-cycle), the outbound supply chains (e.g., the physical distribution of products to the end-customer), the distribution and transportation operation required for serving the customer (Christopher and Lee, 2004; Erhun et al., 2007; Spekman and Davis, 2004; Svensson, 2004). Further, demand side vulnerability drivers can reside in the uncertainty surrounding the random demands of the customers (Nagurney et al., 2005; Tang, 2006b).

Vulnerability drivers on the *supply side* can reside in the supply base, the supplier portfolio or the supplier network (e.g., supplier–supplier relationships, supply base complexity, supply base structure) (Choi and Hong, 2002; Choi and Krause, 2006; Hallikas et al., 2004). When a supplier in the supplier network is vertically integrated by a direct competitor, forcing the termination of the relationship with the buying firm can also increase vulnerability of the supply chain for the buying firm (Chopra and Sodhi, 2004). Next, the characteristics of individual suppliers in a firm's supplier portfolio can influence supply chain vulnerability. This concerns particularly the financial instability of suppliers and the consequences of supplier default, insolvency, or bankruptcy (Babich et al., 2007). Sheffi and Rice (2005) cite the example of the automobile manufacturer Land Rover that found itself in serious trouble after its only supplier of chassis frames, UPF-Thomson, suddenly and unexpectedly folded in 2001. The inability of suppliers to adapt to technological or product design changes may have detrimental effects on the customer's costs and competitiveness (Zsidisin and Ellram, 2003). SCVDs that lie on the buyer–supplier interface include opportunistic behavior from suppliers (particularly in single-source purchasing arrangements) and the dependence on certain suppliers that leaves only a limited room for maneuvering for the buying firm (Giunipero and Eltantawy, 2004; Hallikas et al., 2005; Trevelen and Schweikhart, 1988; Wagner and Johnson, 2004).

Vulnerability drivers in the *supply chain structure* stem to a large degree from the disintegration of supply chains and the globalization (and off-shoring) of value-adding activities (Srai and Gregory, 2008). Because "globalization requires a highly coordinated flow of goods, information, and cash within and across national boundaries" (Bowersox and Calantone, 1998, p. 84) disruptions can have severe impacts on these flows across national boundaries and consequently on supply chain performance (Hendricks and Singhal, 2005; Seshadri and Subrahmanyam, 2005; Wagner and Bode, 2008). When supply chains have to cover a larger number of international markets and regions of the world, the more susceptible they are to natural and man-made disasters (Manuj and Mentzer, 2008; Myers et al., 2006). Furthermore, modern supply chains contain less "slack", with lower inventories, fewer buffers and leaner logistics operations—making supply chains more fragile (McGillivray, 2000; Zsidisin et al., 2005). Likewise, Tang and Tomlin (2008, p. 12) observed that "[l]ong and complex global supply chains are usually slow to respond to changes, and hence, they are more vulnerable to business disruptions".

In sum, the structure of the supply chain, the parties involved on the supply side and the parties involved on the demand side of the supply chain can all be considered major drivers of supply chain vulnerability.

2.4. Supply chain vulnerability at different levels of analysis

Supply chain vulnerability can be measured and managed at different levels, principally an entire economy, an industry, an entire supply chain, or only the focal firm. Likewise, decision makers at these different levels can define measures to reduce supply chain vulnerability. The higher the level, the more difficult it is for an individual firm to influence supply chain vulnerability.

It can be worthwhile to measure the vulnerability on the level of an *economy*. Prominent examples of supply chain disruptions that struck national economies are the 1999 earthquake in Taiwan or Hurricane Katrina that hit the United States in 2005. McKinnon (2006) provides a qualitative analysis of the vulnerability of the UK economy to the temporary disruption of the country's road freight system. He concludes that individual firms can do little to reduce the vulnerability stemming from a temporary shut-down of road freight transportation. Instead, public policy makers would have to understand the vulnerability of supply chains to such a source of risk and take emergency measures in case a disruption occurs. In sum, a measure and a better understanding of supply chain vulnerability for a national economy can result in better informed decisions of policy makers with respect to an economy's supply chain vulnerability.

The next level is the application of the concept of supply chain vulnerability to an *industry*. Supply chain vulnerability can vary among industries. In their study of the impact of supply chain disruptions on operating performance, Hendricks and Singhal (2005) show that industries are affected differently by supply chain disruptions. Other industry-specific examples include the high number of vulnerable suppliers in the automotive industry (Hannon, 2008; Wagner et al., 2009) or the shortages of certain commodities (e.g., electronic components, steel) on the supply market (Carbone, 2000; Stundza, 2005). In Section 4 we calculate SCVIs for different industries and draw conclusions for decision makers from this industry level analysis in Section 5.

A large number of SCRM publications concentrate their concepts and analysis on the *supply chain* (Vanany et al., 2008). For example, the fire at Philips' Albuquerque plant, a supplier of radio-frequency chips for mobile phones, demonstrates how vulnerable nodes in supply chains can influence a firm's performance. As a consequence of the drop in the supply of radio-frequency chips from Philips, mobile phone manufacturer Ericsson suffered a loss of about $400 million (Norrman and Jansson, 2004). In 2005, automotive supplier Robert Bosch failed to detect a defect in the Teflon coating on a small socket. The socket was supplied by Federal Mogul and the contaminated Teflon by DuPont. The part was built into diesel injection pumps for customers like Audi, BMW, and DaimlerChrysler who suffered from standstills of assembly lines and had to recall vehicles (Wagner and Bode, 2006). These examples of vulnerability at the supply chain level are confirmed by the fact that competition is now taking place more between supply chains than between individual firms, especially if value chains are structured globally (Lambert and Cooper, 2000; Lonsdale 1999).

Supply chain vulnerability can also be assessed on the level of the *focal firm*—not taking the consequences of supply chain risks for the other firms involved in the supply chain into account. Many business continuity plans take this perspective (e.g., what should a firm do in case of fire in its production plant?). The firm level of analysis is narrower and fails to consider the risks stemming from a firm's involvement in networks of production and supply.

3. Graph modeling

A major contribution of this research is to quantify the vulnerability by developing and calculating a supply chain vulnerability index. The impact of the SCVDs outlined in Section 2.3 depends on the dynamics of the relationships among the drivers. In other words, the SCVDs have interdependencies. The reason is that vulnerability in one stage of the supply chain can influence the other stages' vulnerability. For instance, lean inventory (i.e., supply chain structure) increases firms' dependency on customers and suppliers; thus it will affect both supply side and demand side if errors in inventory planning were made. Therefore, it is important to consider these interdependencies among the drivers in the modeling effort. Therefore, graph modeling seems an appropriate method to quantify vulnerability and tap the interdependencies.

The idea of using graphs has begun to attract interest in fields from sociology (e.g., Voelkl and Noë, 2008) to TQM (Grover et al., 2004). In the supply chain area, agility, customer sensitivity, supply chain risk alleviation competency, and risk mitigation environment were approached with graph modeling (Faisal et al., 2006a, 2006b, 2007a, 2007b). However, no application in the SCRM context was found.

Graphs have two basic elements: the node (or vertex) and the edge (or link). By considering vulnerability drivers as vertices and the interdependencies between them as edges, a graph can be plotted for a specific supply chain. Graph modeling to measure vulnerability assists in converting supply chain vulnerability to an index. The use of this index will allow supply chain managers to better manage vulnerability. The manager can ascertain the level of total vulnerability that exists and take appropriate measures.

3.1. Weighted directed graphs

Similar to Faisal and colleagues (Faisal et al., 2006a, 2007a, 2007b), we propose that a weighted directed graph and its adjacency matrix can be applied to calculate the SCVI. The interactions among the vulnerability drivers as considered in this article are direction-dependent and thus these interactions and their intensities are represented by a weighted directed edge.

A graph, $G=(V,E)$, consists of two sets, vertices (denoted by V) and edges (denoted by E). E is a set which consists of pairs (u,v) of distinct elements from V (i.e., $E \in V \times V$). Graph G is "directed" if its edge set is composed of *ordered* pairs of vertices. A directed graph that has numeric value (i.e., weight) associated with each edge is defined as *weighted directed graph* (Gibbons, 1985).

3.2. Representation of weighted direct graph

Each graph can be represented either through a graphical shape or an adjacency matrix. "The adjacency matrix of a simple graph is a matrix with rows and columns labeled by graph vertices, with a 1 or 0 in position (a_i, a_j) according to whether a_i and a_j are adjacent or not. For a simple graph with no self-loops, the adjacency matrix must have zero 0s on the diagonal" (Weisstein, 2008). Fig. 3 illustrates a weighted directed graph and its adjacency matrix.

For the weighted directed graph, its adjacency matrix could have in position (a_i, a_j), the weight assigned to the edge connecting a_i and a_j. In our approach, we calculate the adjacency matrix as follows:

$$\begin{cases} a_{i,j} = w(a_i, a_j) & \text{if } i \neq j \\ a_{i,j} = \mu(a_i) & \text{if } i = j \end{cases} \tag{1}$$

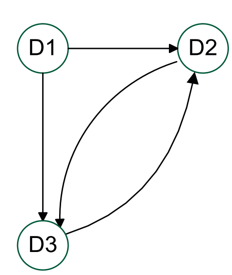
where $w(a_i, a_j) = |cor(a_i, a_j)|$. It is the weight assigned to the edge between a_i and a_j calculated as the absolute value of the correlation between them (i.e., the strength of interdependency between vulnerability driver i and j). And $\mu(a_i)$ is the mean value of a_i (i.e., the expected outcome value for vulnerability driver i).

Although the graph representation clearly shows variables and their interdependencies, the use of the adjacency matrix is preferred to avoid complexity (Faisal et al., 2007a), and also matrices can be stored, retrieved and processed by computer programs such as Excel or Mathematica.

3.3. Supply chain vulnerability index

For calculating the SCVI we propose a four-step algorithm:

Step 1: *Finding graph nodes*: In the first step, the major drivers of supply chain vulnerability (i.e., graph nodes) have to be identified. Faisal et al. (2007a) proposed that this be developed within a "brainstorm" session with academic and industry experts. However, in our approach, we propose combining it with a statistical method. We use factor analysis (i.e., principal component analysis) to extract the main drivers of supply chain



$$\begin{array}{c c} & \begin{array}{ccc} D1 & D2 & D3 \end{array} \\ \begin{array}{c} D1 \\ D2 \\ D3 \end{array} & \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \end{array}$$

Fig. 3. Example of vulnerability digraph representation and its adjacency matrix.

vulnerability (i.e., graph nodes) from more objective and quantitative datasets. In order to calculate the value for SCVDs, the average of the vulnerability variables assigned to a factor should be calculated using the following formula:

$$when \quad i=j : a_{i,j} = \frac{\sum_{k=0}^{n} \mathrm{var}_k}{n} \tag{2}$$

Step 2: *Finding graph's weighted and directed edges*: Next, a correlation analysis must be conducted to reveal the interdependencies (their existence and strength) among SCVDs. For any edges, three characteristics have to be determined: (1) its existence, which is measured by a significant correlation between SCVDs; (2) its strength, which is the absolute value of the correlation; and (3) its direction, which has to be decided by supply chain managers.

Step 3: *Calculating adjacency matrix permanent*: Following the construction of the weighted directed graph, its adjacency matrix has to be developed, as explained above. Similar to Faisal et al. (2007b) we subsequently calculate the matrix permanent value in order to derive our SCVI (Horn and Johnson, 1990; Jerrum et al., 2004). Although the calculation of permanent function is possible for some matrices with approximation, for our purpose the permanent of an $n \times n$ non-negative matrix $A=(a(i,j))$ is calculated as

$$\mathrm{per}(A) = \sum_{\sigma} \prod_{i} a(i, \sigma(i)) \tag{3}$$

where the sum is over all permutations σ of $\{1,2,\ldots,n\}$ (Jerrum et al., 2004). Since permanent cannot be calculated for all the matrices (unlike determinant) there is no predefined or standard module in mathematical software packages. But as we deal with a simple $n \times n$ matrix, we can calculate the permanent of adjacency matrix using Mathematica software.

Step 4: *Comparing different SCVIs*: After repeating steps 1 through 3 at various times to obtain several SCVIs, or calculating SCVIs for different units (e.g., different industries) the different SCVIs that are calculated have to be compared in terms of: (1) graphs' order; (2) graphs' size; and (3) graphs' permanent values. If managers calculated SCVIs for the same supply chain but for different points in time (e.g., before and after the implementation of risk mitigation strategies), they can compare the differences by comparing the SCVIs. If the SCVI decreases, their strategies are effective. But if managers are comparing two different supply chains, then, everything being equal (all the first three steps), supply chains are considered equal in terms of vulnerability; otherwise the one with the higher SCVI is more vulnerable than the other.

4. Application to empirical data

In order to illustrate the application of the proposed approach with quantitative data, we collected data from a large number of firms and calculated SCVIs for different industries. The data were collected through a large-scale survey. The mailing and two follow-ups were sent to a sample of 4946 top-level logistics and supply chain management executives at German firms, resulting in 760 usable responses (response rate 15.4%). Non-response bias was assessed based on the procedure proposed by Armstrong and Overton (1977) indicating absence of non-response bias. The sample covered eight different industries. The firms' annual sales ranged from less than US$10 million to US$90 billion (mean US$60.3 million), and the number of employees from <100 to 430,000 (mean 2913). Most of the respondents hold executive positions in logistics and supply chain management (37.5%), or were C-level executives and owners (23.8%). On average, the respondents have worked in their position for 7.0 years and have been with their firm for 10.9 years. A more detailed breakdown of the sample can be found in Table 1.

Respondents were asked to indicate how their firms had been negatively affected by supply chain disruptions and how their supply chain design was structured (i.e., the drivers of supply chain vulnerability).

As outlined earlier, the first task has to be the extraction of major SCVDs out of vulnerability variables. In order to accomplish this we applied principal component analysis. The factor analysis identifies groups of inter-related supply chain vulnerability variables, reduces the number of variables by combining several variables into a single factor, and identifies the factors (in our case the SCVDs). In our illustrative example we had information pertaining to 10 supply chain vulnerability variables that were aggregated to overarching SCVD factors. There are certainly more variables that could be considered as drivers of supply chain vulnerability (e.g., variables pertaining to information risks or process risks) but we did not have data about them in our illustrative data set. The assignment of the 10 supply chain vulnerability variables to the aggregated SCVDs is presented in Table 2. We were able to assign all available variables to the three SCVDs. Table 3 presents the differences in SCVDs' mean values between industries.

After calculating the value of SCVDs for each record with formula (2), the correlation analysis was applied separately for each industry. The directions of edges were determined based on a review of the pertinent supply chain management literature and the judgments of six supply chain risk experts from academia and industry: two academics who had done extensive research in the area of supply chain risk, two managers from industrial firms who in the past assessed their firms' supply chain risk, and two consultants from large top-management consulting firms who had supported clients in various industries in setting up supply chain risk management systems. These experts judged the directions of the edges independently. In case of disagreement, a member of the research team revisited the expert to come to a final conclusion about the directions. From the outcome of the correlation analysis (strength of the relationships) and the expert judgments (direction of the relationships), the graphs and consequently the SCVIs were calculated for each industry (Fig. 4).

Table 1
Sample composition.

Industries	Frequency	Percentage
1—Food and consumer goods	61	8.0
2—Engineered products	241	31.7
3—Automotive	85	11.2
4—Information and communication technology (ICT)	50	6.6
5—Process manufacturing	107	14.1
6—Wholesale and retail	67	8.8
7—Logistics	130	17.1
8—Others	18	2.4
Na	1	0.1
Annual revenues (in US$)		
<10 million	113	14.9
10 million–under 50 million	182	23.9
50 million–under 100 million	124	16.3
100 million–under 250 million	112	14.7
250 million–under 500 million	66	8.7
500 million–under 1 billion	51	6.7
1 billion–under 10 billion	55	7.2
10 billion or more	38	5.0
Na	19	2.5

5. Discussion and implications

In this article we demonstrated that graphs can be used as visual maps that facilitate the understanding of supply chain vulnerability and support decision making in SCRM. When supply chain managers inspect the vulnerability graph, they can more easily understand the relationship between different drivers. They can set priorities and execute appropriate measures for risk mitigation. Because "supply chain risk management is not for free, managers are compelled to seek an efficient allocation of risk management resources and a reasonable cost-benefit trade-off" (Wagner and Bode, 2009, p. 286). Given managers' limited amount of resources such as time and money, the graph theoretical approach presented in this article can help them to make effective and efficient decisions and allocate an appropriate amount of resources to a particular supply chain vulnerability driver.

For instance, the graph in Fig. 5 shows vulnerabilities and their interdependencies in a supply chain. Managers can see that D_1 influences two other drivers and everything else being equal, it should be mitigated earlier than D_4. Another important aspect is that $In\text{-}deg(D_3)=3$ and the $Out\text{-}deg(D_3)=0$—hence it is called a "sink"—which means that D_3 can only be influenced by three other drivers and cannot influence others. Considering the graph

Table 2
Supply chain vulnerability drivers.

Drivers of supply chain vulnerability	Main variables
Demand side	Short products' life cycles Customers' dependency Low in-house production
Supply side	Small supply base Suppliers' dependency Single sourcing
Supply chain structure	Global sourcing network Lean inventory Supply chain complexity Centralized storage of finished products

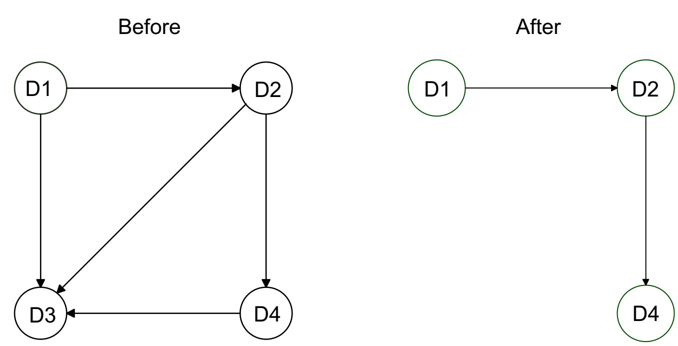


Fig. 5. Vulnerability graph, before and after applying SCRM.

Table 3
Supply chain vulnerability drivers' mean for different industries.

	Industries							
	1	2	3	4	5	6	7	8
Demand side	2.92	2.49	2.89	3.01	2.67	2.64	2.96	2.77
Supply side	2.54	2.93	3.05	2.71	2.91	2.45	2.45	2.50
Supply chain structure	3.22	3.24	3.28	3.17	3.28	3.21	2.72	2.45

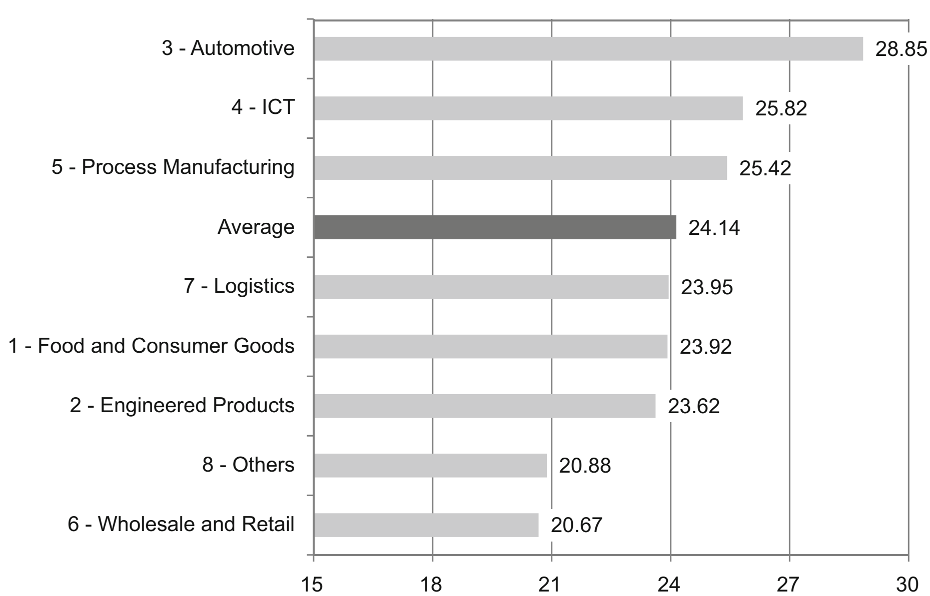


Fig. 4. Supply chain vulnerability indices (SCVIs) for different industries.

nodes and edges, supply chain managers can apply risk management methods and implement mitigation strategies to omit or alleviate some of the vulnerability drivers. Fig. 5 shows the graph after D_3 has been omitted. As one can see, the resulting graph contains less vulnerability than it did prior to implementing the measures.

With the SCVI, we contribute a metric that can be readily applied in SCRM. Supply chain managers can assess the vulnerability of supply chains (e.g., across and between supply chains, or over time) and compare the effectiveness of different SCRM measures. From the comparison of SCVIs between industries, supply chain managers can identify industries with an overall low supply chain vulnerability, and potentially apply the supply chain risk management approaches of these industries as "best practice" in their own firms.

In addition, the implementation of such a supply chain vulnerability measurement system in a firm will foster an organizational culture and management style that help firms to increase their employees' awareness of supply chain risks (Bititci et al., 2006). A "risk management culture" is a major consideration in reliable supply chains when firms have to respond to disruptions (Roberts, 1990).

Besides these general discussions and recommendations from our graph theoretical approach, it is warranted to discuss some noteworthy insights pertaining to the empirical data. The purpose of the data collected from 760 firms in Germany was to illustrate the application of graph theory.

The inspection of the SCVIs reveals that firms in the automotive industry are exposed to the highest supply chain vulnerability (SCVI=28.85), followed by firms producing and selling information and communication technology (ICT) (SCVI=25.82), and firms in process manufacturing (e.g., chemicals, oil and gas) (SCVI=25.42). Therefore, managers in these industries must be particularly concerned with supply chain disruptions. A similarity that can be observed is that for all three industries, supply chain structure (e.g., global setup and complexity of the supply chains), is the main driver of supply chain vulnerability. However, these industries differ in a way that in the ICT industry the demand (customer) side represents a higher degree of vulnerability than the supply (supplier) side, whereas in the automotive and process manufacturing industries, the vulnerability stemming from the supply side contributes to the firms' overall vulnerability to a higher degree than the demand (customer) side. Therefore, managers in the automotive and process manufacturing industries should aim to reduce the risk stemming from the supply side.

Firms from the logistics, food and consumer goods and engineered products industries in our sample with SCVIs of 23.95, 23.92, and 23.62, have on average about the same level of supply chain vulnerability. For food and consumer goods firms and engineered products firms the supply chain structure is also the most important driver of supply chain vulnerability, and for logistics firms it is the demand side (the logistics service firms' customers).

The German wholesale and retail firms' supply chain vulnerability is the lowest of all industries covered in this survey (SCVI=20.67). Therefore, such trade firms must be less concerned with supply chain vulnerability than manufacturing and logistics service firms.

Insights from modeling and measuring supply chain vulnerability with the method we proposed in this article can also help other firms that are not directly involved in the supply chains, such as insurance companies. They might be interested in measuring and drawing comparisons of supply chain vulnerability in different industries in order to set their premiums (i.e., applying higher premiums to industries where vulnerability and hence chance of disruption and loss is higher).

6. Conclusions

In this article we presented a novel approach to measure and manage supply chain vulnerability. At its heart we utilized graph modeling to convert the "fuzzy" construct of supply chain vulnerability to an index (the SCVI). Our research hints at the advantages of using quantitative data to model and measure supply chain vulnerability, and closes a gap that exists with respect to the quantification of the multi-dimensional construct "supply chain vulnerability" (Kleindorfer and Saad, 2005).

Despite these merits, our research is not without limitations. First, the applicability of our proposed approach heavily depends on the availability of data that quantifies the drivers of supply chain vulnerability. While we have collected data on a number of drivers of supply chain vulnerability from 760 firms, practitioners will have difficulties obtaining such data for the supply chains their firms are involved in. Therefore, future research should investigate means of obtaining data other than through surveying firms (Boyer and Swink, 2008). Innovative approaches to tap available data sources to feed our graph model are needed.

Second, the reliability of the direction of the edges in the graphs depends on the quality of the experts' judgment (Ayyub, 2001). Research is needed to determine if the experts' judgment (i.e., perception about the relationships among the drivers) is a good estimator of the "true" but unobservable relationships.

Third, while our graph theoretical approach lends itself to an ongoing analysis of supply chain vulnerability, we have applied it to a cross-sectional data set. A better understanding of the dynamic nature of supply chain vulnerability over time and the consequences for our proposed approach is necessary and up to future research (Singer and Willett, 2003).

Fourth, while we present one novel method to measure and illustrate supply chain vulnerability, there are other methods that might suit this task. The literature suggests a few approaches to quantify supply chain risk (Handfield et al., 2007) as well as supply chain risk maps or risk portfolios—the graphical representation of disruption probabilities and the associated revenue impact of supply chain risk (Manuj and Mentzer, 2008; Waters, 2007). Asbjørnslett (2009) sketches a generic fishbone diagram of internal and external factors contributing to supply chain vulnerability. Naim et al. (2002) provide a diagnostic tool ("health check") for supply chains with graphical representations of uncertainty scores for several uncertainty sources (including supply side and demand side sources). Future research should further develop these methods to assess supply chain vulnerability and develop new ones, and compare such alternative methods to graph theory modeling in order to determine the superior approach—similar to what has been done in other fields (e.g., Gutierrez et al., 2008).

On the whole, our study lays the important groundwork for quantitative approaches to measure supply chain vulnerability. Managers should mitigate vulnerability proactively and collaboratively with other members of the supply chain (e.g., suppliers, suppliers' suppliers, customers, customers' customers) to reduce supply chain risk (Bogataj and Bogataj, 2007) and subsequently improve financial performance of the firm (Hendricks and Singhal, 2005). Assessing the vulnerability of their supply chains using graph theory can support them in this effort.

Appendix A. Algorithm for calculating the SCVI

Step	Graph	SCRM context	Tool	Input	Procedure	Output	Notes
1	Finding graph nodes	Finding supply chain vulnerability drivers (SCVD)	Expert opinion or statistics methods (e.g., factor analysis)	Supply chain vulnerability variables	Asking experts for their opinion and/or running factor analysis to find major SCVDs, then calculating average of variables to have the value for major drivers	Major supply chain vulnerability drivers	
2	Finding graph's weighted and directed edges	Finding SCVDs' interdependency (existence, strength, and direction)	Correlation analysis or expert opinion	Major supply chain vulnerability drivers	Running correlation analysis and/or asking experts for their opinion to find significant correlation between SCVDs	SCVDs' interdependency (existence, strength, and direction)	Negative correlations have to be considered as their absolute values
3	Calculating the adjacency matrix permanent	Calculating supply chain vulnerability index (SCVI)	MATH function	Weighted directed graph of SCVDs	Calculating $Permanent(A_{n*n})$ n: Order of graph a_{ij} *when* $i \neq j$: $\lvert Corr(a_i, a_j)\rvert \times 5$ a_{ij} *when* $i=j$: $Mean(a_{ij})$	Supply chain vulnerability index (SCVI)	$Mean(a_{ij})$ has to be in 0–5 range
4	Comparing different graphs	Comparing different groups (e.g., industries, firms' sizes, countries, product types)	MATH function	Weighted directed graphs of SCVDs	(1) Comparing graphs' order (2) Comparing graphs' size (3) Comparing graphs' permanent values (4) If everything is equal, then A and B are equally vulnerable, otherwise one is more vulnerable than the other	Comparison of supply chain vulnerability among different groups	If graphs' nodes are different, then their type and edge direction should be considered

References

Armstrong, J.S., Overton, T.S., 1977. Estimating nonresponse bias in mail surveys. Journal of Marketing Research 14 (3), 396–402.

Asbjørnslett, B.E., 2009. Assessing the vulnerability of supply chains. In: Zsidisin, G.A., Ritchie, B. (Eds.), Supply Chain Risk: A Handbook of Assessment, Management and Performance. Springer, New York, pp. 15–33.

Ayyub, B.M., 2001. Elicitation of Expert Opinions for Uncertainty and Risks. CRC Press, Boca Raton, FL.

Babich, V., Burnetas, A.N., Ritchken, P.H., 2007. Competition and diversification effects in supply chains with supplier default risk. Manufacturing & Service Operations Management 9 (2), 123–146.

Bititci, U.S., Mendibil, K., Nudurupati, S., Garengo, P., Turner, T., 2006. Dynamics of performance measurement and organisational culture. International Journal of Operations & Production Management 26 (12), 1325–1350.

Bogataj, D., Bogataj, M., 2007. Measuring the supply chain risk and vulnerability in frequency space. International Journal of Production Economics 108 (1–2), 291–301.

Bowersox, D.J., Calantone, R.J., 1998. Executive insight: global logistics. Journal of International Marketing 6 (4), 83–93.

Boyer, K.K., Swink, M.L., 2008. Empirical elephants—why multiple methods are essential to quality research in operations and supply chain management. Journal of Operations Management 26 (3), 338–344.

Carbone, J., 2000. Computer industry buyers deal with tight supplies. Purchasing 129 (5), 45–48.

Centre for Research on the Epidemiology of Disasters, 2004. EM-DAT: The OFDA/CRED International Disaster Database. Université Catholique de Louvain, Brussels.

Chen, I.J., Paulraj, A., 2004. Towards a theory of supply chain management: the constructs and measurements. Journal of Operations Management 22 (2), 119–150.

Choi, T.Y., Hong, Y., 2002. Unveiling the structure of supply networks: case studies in Honda, Acura, and DaimlerChrysler. Journal of Operations Management 20 (5), 469–493.

Choi, T.Y., Krause, D.R., 2006. The supply base and its complexity: implications for transaction costs, risks, responsiveness, and innovation. Journal of Operations Management 24 (5), 637–652.

Chopra, S., Sodhi, M., 2004. Avoiding supply chain breakdown. MIT Sloan Management Review 46 (1), 53–62.

Christopher, M., Lee, H.L., 2004. Mitigating supply chain risk through improved confidence. International Journal of Physical Distribution & Logistics Management 35 (4), 388–396.

Christopher, M., Peck, H., 2004. Building the resilient supply chain. International Journal of Logistics Management 15 (2), 1–13.

Colema, L., 2006. Frequency of man-made disasters in the 20th century. Journal of Contingencies and Crisis Management 14 (1), 3–11.

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.

Erhun, F., Gonçalves, P., Hopman, J., 2007. The art of managing new product transitions. MIT Sloan Management Review 48 (3), 73–80.

Faisal, M.N., Banwet, D.K., Shankar, R., 2006a. Mapping supply chains on risk and customer sensitivity dimensions. Industrial Management & Data Systems 106 (6), 878–895.

Faisal, M.N., Banwet, D.K., Shankar, R., 2006b. Supply chain risk mitigation: modeling the enablers. Business Process Management Journal 12 (4), 535–552.

Faisal, M.N., Banwet, D.K., Shankar, R., 2007a. An approach to measure supply chain agility. International Journal of Industrial and Systems Engineering 2 (1), 79–98.

Faisal, M.N., Banwet, D.K., Shankar, R., 2007b. Quantification of risk mitigation environment of supply chains using graph theory and matrix methods. European Journal of Industrial Engineering 1 (1), 22–39.

Gibbons, A., 1985. Algorithmic Graph Theory. Cambridge University Press, Cambridge.

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.

Grover, S., Agrawal, V.P., Khan, I.A., 2004. A digraph approach to TQM evaluation of an industry. International Journal of Production Research 42 (19), 4031–4053.

Gutierrez, R.S., Solis, A.O., Mukhopadhyay, S., 2008. Lumpy demand forecasting using neural networks. International Journal of Production Economics 111 (2), 409–420.

Hallikas, J., Karvonen, I., Pulkkinen, U., Virolainen, V.-M., Tuominen, M., 2004. Risk management processes in supplier networks. International Journal of Production Economics 90 (1), 47–58.

Hallikas, J., Puumalainen, K., Vesterinen, T., Virolainen, V.-M., 2005. Risk-based classification of supplier relationships. Journal of Purchasing & Supply Management 11 (2–3), 72–82.

Handfield, R.B., Blackhurst, J., Elkins, D., Craighead, C.W., 2007. A framework for reducing the impact of disruptions to the supply chain: observations from multiple executives. In: Handfield, R.B., McCormack, K.P. (Eds.), Supply Chain Risk Management: Minimizing Disruption in Global Sourcing. Taylor and Francis, Boca Raton, FL, pp. 29–49.

Hannon, D., 2008. Survival lessons from automotive buyers. Purchasing 137 (11), 51–56.

Hauser, L.M., 2003. Risk-adjusted supply chain management. Supply Chain Management Review 7 (6), 64–71.

Hendricks, K.B., Singhal, V.R., 2003. The effect of supply chain glitches on shareholder wealth. Journal of Operations Management 21 (5), 501–522.
Hendricks, K.B., Singhal, V.R., 2005. Association between supply chain glitches and operating performance. Management Science 51 (5), 695–711.
Horn, R.A., Johnson, C.R., 1990. Matrix Analysis. Cambridge University Press, New York.
Jerrum, M., Sinclair, A., Vigoda, E., 2004. A polynomial-time approximation algorithm for the permanent of a matrix with nonnegative entries. Journal of the ACM 51 (4), 671–697.
Jüttner, U., Peck, H., Christopher, M., 2003. Supply chain risk management: outlining an agenda for future research. International Journal of Logistics: Research and Applications 6 (4), 197–210.
Kleindorfer, P.R., Saad, G., 2005. Managing disruption risks in supply chains. Production and Operations Management 14 (1), 53–68.
Lambert, D.M., Cooper, M.C., 2000. Issues in supply chain management. Industrial Marketing Management 29 (1), 65–83.
Lee, H.L., 2004. The triple-A supply chain. Harvard Business Review 82 (10), 102–112.
Lonsdale, C., 1999. Effectively managing vertical supply relationships: a risk management model for outsourcing. Supply Chain Management: An International Journal 4 (4), 176–183.
Manuj, I., Mentzer, J.T., 2008. Global supply chain risk management. Journal of Business Logistics 29 (1), 133–155.
Martha, J., Subbakrishna, S., 2002. Targeting a just-in-case supply chain for the inevitable next disaster. Supply Chain Management Review 6 (5), 18–23.
McGillivray, G., 2000. Commercial risk under JIT. Canadian Underwriter 67 (1), 26–30.
McKinnon, A., 2006. Life without trucks: the impact of a temporary disruption of road freight transport on a national economy. Journal of Business Logistics 27 (2), 227–250.
Munich Re, 2006. Annual Review: Natural Catastrophes 2005. Munich Re Publications, Munich.
Myers, M.B., Borghesi, A., Russo, I., 2006. Assessing the global environment. In: Mentzer, J.T., Myers, M.B., Stank, T.P. (Eds.), Handbook of Global Supply Chain Management. Sage Publications, Thousand Oaks, CA, pp. 39–49.
Nagurney, A., Cruz, J., Dong, J., Zhang, D., 2005. Supply chain networks, electronic commerce, and supply side and demand side risk. European Journal of Operational Research 164 (1), 120–142.
Naim, M.M., Childerhouse, P., Disney, S.M., Towill, D.R., 2002. A supply chain diagnostic methodology: determining the vector of change. Computers & Industrial Engineering 43 (1–2), 135–157.
Norrman, A., Jansson, U., 2004. Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident. International Journal of Physical Distribution & Logistics Management 34 (5), 434–456.
Peck, H., 2005. The drivers of supply chain vulnerability: an integrated framework. International Journal of Physical Distribution & Logistics Management 35 (4), 210–232.
Roberts, K.H., 1990. Some characteristics of high reliability organizations. Organization Science 1 (2), 160–176.
Seshadri, S., Subrahmanyam, M., 2005. Introduction to the special issue on "Risk Management in Operations". Production and Operations Management 14 (1), 1–4.
Sheffi, Y., Rice Jr., J.B., 2005. A supply chain view of the resilient enterprise. MIT Sloan Management Review 47 (1), 41–48.
Sheffi, Y., 2005. The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage. MIT Press, Cambridge, MA.
Singer, J.D., Willett, J.B., 2003. Applied Longitudinal Data Analysis: Modeling Change and Event Occurrence. Oxford University Press, Oxford.
Spekman, R.E., Davis, E.W., 2004. Risky business: expanding the discussion on risk and the extended enterprise. International Journal of Physical Distribution & Logistics Management 34 (5), 414–433.
Srai, J.S., Gregory, M., 2008. A supply network configuration perspective on international supply chain development. International Journal of Operations & Production Management 28 (5), 386–411.
Stundza, T., 2005. Supplies tighten as aviation soars. Purchasing 134 (16) 36B9–36B12.
Svensson, G., 2002. A conceptual framework of vulnerability in firms' inbound and outbound logistics flows. International Journal of Physical Distribution & Logistics Management 32 (2), 110–134.
Svensson, G., 2004. Vulnerability in business relationships: the gap between dependence and trust. Journal of Business and Industrial Marketing 19 (7), 469–483.
Tang, C.S., 2006a. Robust strategies for mitigating supply chain disruptions. International Journal of Logistics: Research and Applications 9 (1), 33–45.
Tang, C.S., 2006b. Perspectives in supply chain risk management. International Journal of Production Economics 103 (2), 451–488.
Tang, C.S., Tomlin, B., 2008. The power of flexibility for mitigating supply chain risks. International Journal of Production Economics 116 (1), 12–27.
Trevelen, M., Schweikhart, S.B., 1988. A risk/benefit analysis of sourcing strategies: single vs. multiple sourcing. Journal of Operations Management 7 (4), 93–114.
Vanany, I., Zailani, S., Pujawan, N., 2008. Supply chain risk management: literature review and future research. International Journal of Information Systems and Supply Chain Management 2 (1), 16–33.
Voelkl, B., Noë, R., 2008. The influence of social structure on the propagation of social information in artificial primate groups: a graph-based simulation approach. Journal of Theoretical Biology 252 (1), 77–86.
Wagner, S.M., Bode, C., 2006. An empirical investigation into supply chain vulnerability. Journal of Purchasing & Supply Management 12 (6), 301–312.
Wagner, S.M., Bode, C., 2008. An empirical examination of supply chain performance along several dimensions of risk. Journal of Business Logistics 29 (1), 307–325.
Wagner, S.M., Bode, C., 2009. Dominant risks and risk management practices in supply chains. In: Zsidisin, G.A., Ritchie, B. (Eds.), Supply Chain Risk: A Handbook of Assessment, Management and Performance. Springer, New York, pp. 271–290.
Wagner, S.M., Bode, C., Koziol, P., 2009. Supplier default dependencies: empirical evidence from the automotive industry. European Journal of Operational Research 199 (1), 150–161.
Wagner, S.M., Johnson, J.L., 2004. Configuring and managing strategic supplier portfolios. Industrial Marketing Management 33 (8), 717–730.
Waters, D., 2007. Supply Chain Risk Management: Vulnerability and Resilience in Logistics. Kogan Page, London.
Weisstein, E.W., 2008. Adjacency matrix. In: Wolfram MathWorld. Wolfram Research Inc., Oxfordshire. Available at: ⟨http://mathworld.wolfram.com/AdjacencyMatrix.html⟩.
Zsidisin, G.A., Ellram, L.M., 2003. An agency theory investigation of supply risk management. Journal of Supply Chain Management 39 (3), 15–27.
Zsidisin, G.A., Ragatz, G.L., Melnyk, S.A., 2005. The dark side of supply chain management. Supply Chain Management Review 9 (2), 46–52.