Modeling supplier risks using Bayesian networks

Archie Lockamy III
Brock School of Business, Samford University, Birmingham, Alabama, USA, and
Kevin McCormack
College of Management, North Carolina State University, Raleigh, North Carolina, USA

Received 14 June 2011
Revised 16 August 2011
Accepted 17 August 2011

Abstract

Purpose – To counteract the effects of global competition, many organizations have extended their enterprises by forming supply chain networks. However, as organizations increase their dependence on these networks, they become more vulnerable to their suppliers' risk profiles. The purpose of this paper is to present a methodology for modeling and evaluating risk profiles in supply chains via Bayesian networks.

Design/methodology/approach – Empirical data from 15 casting suppliers to a major US automotive company are analyzed using Bayesian networks. The networks provide a methodological approach for determining a supplier's external, operational, and network risk probability, and the potential revenue impact a supplier can have on the company.

Findings – Bayesian networks can be used to develop supplier risk profiles to determine the risk exposure of a company's revenue stream. The supplier risk profiles can be used to determine those risk events which have the largest potential impact on an organization's revenues, and the highest probability of occurrence.

Research limitations/implications – A limitation to the use of Bayesian networks to model supply chain risks is the proper identification of risk events and risk categories that can impact a supply chain.

Practical implications – The methodology used in this study can be adopted by managers to formulate supply chain risk management strategies and tactics which mitigate overall supply chain risks.

Social implications – The methodology used in this study can be used by organizations to reduce supply chain risks which yield numerous societal benefits.

Originality/value – As part of a comprehensive supplier risk management program, organizations along with their suppliers can develop targeted approaches to minimize the occurrence of supply chain risk events.

Keywords United States of America, Automotive industry, Supply chain management, Modelling, Suppliers, Supply networks, Supplier risks, Risk events, Supplier risk profiles, Bayesian networks

Paper type Research paper

1. Introduction

The twenty-first century business environment is characterized by increasing levels of global competition, demanding customers and employees, shrinking product lifecycles, and decreasing acceptable response times. In an effort to counteract these market forces, many organizations have extended their enterprises outside of their legal boundaries by forming competitive networks of organizations known as supply chains. Supply chains represent a coordinated network of organizations interacting to provide a product or service to the end-user. Supply chain management (SCM) seeks to enhance

Industrial Management & Data Systems
Vol. 112 No. 2, 2012
pp. 313-333

0263-5577
DOI 10.1108/02635571211204317

the competitive performance of the network via the internal integration of an organization's functional areas, and by effectively linking them to the external operations of suppliers, customers, and other network members (Kim, 2006). Additionally, Sawhney *et al.* (2006) identified supply chains as a mechanism for fostering business innovation within organizations through the adoption of streamlined information flows, restructured business processes, and enhanced collaboration among network members.

As organizations increase their dependence on integrated supply networks, they become more susceptible to supply chain disruptions. The associated financial and operational risks of supply chain disruptions represent a major concern to organizations competing in the global economy (Craighead *et al.*, 2007). For example, Kleindorfer and Saad (2005) note that due to events such as the Taiwan earthquake of 1999, the 2001 terrorist attack on the World Trade Center, and the 2003 blackout in the Northeastern sector of the USA, organizations have placed an increased emphasis on supply chain risk management (SCRM). Moreover, the massive product recall and production shutdown experienced by the Toyota Motor Corporation in January 2010 had an adverse impact on its supply chain as well as supplier and customer relations, also illustrating the need for effective risk management within supply chains (Atkinson, 2010). Finally, increased risks due to the 2008-2009 global financial crises pose a new challenge faced by supply chain managers in their quest to mitigate supply chain threats along with possible disruptions to their supply chains (Murphy, 2009).

The long-run negative effect on an organization's stock price due to supply chain disruptions has been documented through a study by Hendricks and Singhal (2005), illustrating a negative 40 percent return two years after the date of the disruption announcement. Additionally, Cousins *et al.* (2004) argue that there are also important non-financial consequences of supply chain disruptions, such as a reduction in product quality, damage to property and equipment, lost reputation among customers, suppliers, and the wider public and delivery delays. Thus, it has become increasingly important for organizations to assess the risks associated with their supply chains.

1.1 Purpose

The purpose of this article is to introduce a methodology for modeling and evaluating risks in supply chains, based on a study of 15 casting suppliers to a major US automotive company. The methodology uses Bayesian networks for the creation of risk profiles for each supplier. The networks are used to determine a supplier's external, operational and network risk probability, and the potential revenue impact a supplier can have on the organization as measured by value-at-risk (VAR). The methodology is offered as a tool to assist managers in the formulation of strategies and tactics to mitigate overall supply chain risks.

1.2 Organization

The paper is organized as follows. Section 1 provided the motivation for and purpose of the paper. A discussion on SCM and supply chain risks is provided in Sections 2 and 3, respectively. Section 4 contains an overview of the research methodology and model used in this study. Section 5 contains the results of the research. Proposed managerial actions based upon the results of the study are provided in Section 6. Conclusions are offered in Section 7. Finally, implications regarding study limitations and directions for future research are presented in Sections 8 and 9, respectively.

2. Supply chain management

SCM involves the management of information, material, and cash flows across multiple functional areas both within and among organizations (Faisal *et al.*, 2006a). A growing number of organizations are adopting SCM to improve competitiveness (Gunasekaran *et al.*, 2008; Li *et al.*, 2006; Singh *et al.*, 2005). Additionally, the chain-wide deployment of SCM practices consistent with the above-mentioned philosophy is needed to accrue maximum benefits to its members.

In order to realize the potential benefits of SCM, organizations are required to make fundamental changes to their business focus (Kopczak and Johnson, 2003). These changes include an emphasis on cross-functional and cross-enterprise integration (Chen and Kang, 2007); the effective management of the flow of physical goods through suppliers, manufacturers, distributors, and retailers for increased value to end customers (Jammernegg and Reiner, 2007); and the ability to acquire and manage reliable demand information (Croxton *et al.*, 2002).

Effective SCM should result in enhanced customer satisfaction and value, along with improved supply chain reactivity (Gaudenzi and Borghesi, 2006). Supply chain reactivity refers to the network's ability to compress lead times, adapt to unanticipated changes in demand, and to cope with environmental uncertainty in the market place. However, the interdependencies created among participating organizations via integrated supply networks make them more vulnerable to supply chain disruptions.

3. Supply chain risks

Supply chain risks are derived from both internal and external sources of uncertainty (Cucchiella and Gastaldi, 2006). Internal sources of uncertainty may include changes in capacity availability, interruptions in information flows, and reductions in operational efficiencies. The actions of competitors, price fluctuations, changes in the political environment, and variations in supplier quality are some of the external sources of uncertainty leading to increased supply chain risks. These sources of uncertainty may be viewed as "risk events" which can potentially result in supply chain disruptions which impede overall supply chain performance. Chopra and Sodhi (2004) note that managers must first understand the various risk categories as well as the events and conditions that drive them before they can devise an effective means of reducing supply chain risks.

The risk of disruptions caused both from factors within supply chains and from outside environmental forces is of main concern to both practitioners and researchers. SCRM is, therefore, a field of growing importance and is aimed at developing approaches for the identification, assessment, analysis, and treatment of areas of vulnerability and risk in supply chains (Neiger and Rotaru, 2009). Various trends that increase exposure to risks, such as the increased use of outsourcing, globalization, supplier-base reductions, reduced inventory buffers, increased demand for on-time deliveries, and shorter product life cycles (Norrman and Jansson, 2004), are elevating the importance of SCRM. This is highlighted by several practical examples of the high costs of improper preparation and response to various supply chain risk events cited by Chopra and Sodhi (2004).

Currently, SCRM approaches are attempting to measure either supplier attributes or supply chain structures to compare suppliers and predict disruptions. The results are then used to prepare proper mitigation and response strategies associated with these suppliers. Most often SCRM is a formal process that involves identifying potential losses, understanding the likelihood of potential losses, and assigning significance to these losses (Giunipero and Eltantawy, 2004). A typical example of such an approach is the procurement risk assessment and mitigation) methodology, developed by the Dow Chemical Company to measure SC risk and its impact. This approach examines the following factors of a supply chain: supply market risk, supplier risk, organization risk, and supply strategy risk (Hackett Group, 2007).

A variety of approaches are offered in the research literature for categorizing supply chain risks. For example, supply chain risk can be divided, according to its source, in the following manner: demand-side risks resulting from disruptions emerging from downstream supply chain operations (Suttner, 2005); supply-side risks residing in purchasing, supplier activities, and supplier relationships; and catastrophic risks that, when they materialize, have a severe impact in terms of magnitude in the area of their occurrence (Wagner and Bode, 2006). Additionally, Treleven and Schweikhart (1988) classify risks into five categories, connected with disruption, price, inventories and schedule, technology, and quality.

Kleindorfer and Wassenhove (2003) define supply chain co-ordination and supply disruptions as categories of supply chain risks, while Paulsson (2004) classifies supply chain risks as operational disturbances, tactical disruptions, and strategic uncertainties. Giunipero and Eltantawy (2004) categorize these risks based upon conditions which result in their creation, such as political events, product availability, transportation distances, changes in technology, and labor markets, financial instability, and management turnover. Supply chain disruptions, delays, systems, forecasts, intellectual property, procurement, receivables, inventory, and capacity are classifications for supply chain risks offered by Chopra and Sodhi (2004).

Zsidisin *et al.* (2005) define supply risk as the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing organization to meet customer demand or cause threats to customer life and safety. Wu *et al.* (2006) states that inbound supply risk is defined as the potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market, resulting in the inability of the purchasing organization to meet customer demand and as involving the potential occurrence of events associated with inbound supply that can have significant detrimental effects on the purchasing organization. Nagurney *et al.* (2005) define demand side risk as represented by the uncertainty surrounding the random demands which often occur at the retailer stage of the supply chain.

Handfield and McCormack (2007) classify supply chain risks from the perspectives of suppliers, customers, and the company. A supplier facing perspective examines the network of suppliers, their markets, and their risk relationships with the "company". A customer facing perspective examines the network of customers and intermediaries, their markets, and their risk relationships with the "company". Finally, an internal facing perspective examines risk relationships with respect to the company, its network of assets, processes, products, systems, and people, as well as its markets. The purpose of this study is to present a methodology for analyzing risks associated with suppliers using Bayesian networks. Therefore, this research study uses the supplier facing perspective in the analysis of supply chain risk. Additionally, this study further classifies risk into three categories: operational, network, and external. In the financial industry, operational risk is defined as the risk of loss resulting from inadequate or failed internal processes, people, and systems, or from external events (Basel Committee on Banking Supervision, 2006). Examples of operational risks are quality, delivery, and service problems. Network risk is defined as risk resulting from the structure of the supplier network such as ownership, individual strategies of the suppliers, and the supplier's supply network agreements (Wu *et al.*, 2006). External risks are defined as events driven by external forces such as weather, earthquakes, political, regulatory, and market forces (Wagner and Bode, 2006).

4. Research methodology

This study incorporates the use of a risk assessment model, surveys, data collection from internal and external company sources, and Bayesian networks. The networks were used to create risk profiles for the 15 casting suppliers. Additionally, the study adopts the risk categories outlined by Handfield and McCormack (2007). An overview of Bayesian networks is given in Section 4.1. Discussions on the assessment model, study participants, and data sample are provided in Sections 4.2 and 4.3, respectively. Finally, the research model used in the study is discussed in Section 4.4.

4.1 Bayesian networks

Bayesian networks are annotated directed acyclic graphs that encode probabilistic relationships among nodes (variables) of interest in an uncertain reasoning problem (Pai *et al.*, 2003). The representation describes these probabilistic relationships and includes a qualitative structure that facilitates communication between a user and a system incorporating a probabilistic model. Bayesian networks have evolved as an effective tool for analyzing uncertainty. When these networks were first introduced, assigning the full probability distributions manually to them was time intensive. However, advancements in computational power along with the development of heuristic search techniques to find events with the highest probability have enhanced the development and understanding of Bayesian networks.

Pai *et al.* (2003) were among the first researchers to analyze supply chain risks using Bayesian networks. Their study examined the risk profile associated with a US Department of Defense (DoD) supply chain for trinitrotoluene (TNT). The supply chain was comprised of TNT recovery plants, storage facilities, and ammunition depots. Using Bayesian networks, the researchers were able to establish risk factors and acceptable risk limits for all assets contained in the DoD supply chain. Bayesian networks have also been used to conduct diagnostics (Kauffmann *et al.*, 2002; Kao *et al.*, 2005), cost optimization studies (Narayanan *et al.*, 2005), and flexibility analysis (Wu, 2005; Milner and Kouvelis, 2005) in supply chains.

Since the work of Pai *et al.* (2003), researchers have continued to explore the use of Bayesian networks to analyze and manage supply chain risks. For example, there have been a number of studies which examine the use of Bayesian networks as part of a decision support system to manage such risks (Li and Chandra, 2007; Meixell *et al.*, 2008; Shevtshenko and Wang, 2009; Makris *et al.*, 2011; Taskin and Lodree, 2011). Studies by Tomlin (2009) and Chen *et al.* (2010) demonstrate how Bayesian networks can be used to manage supply chain uncertainty. The integration of Bayesian networks into supply chain forecasting methodologies to mitigate risks has also been examined by several researchers (Yelland, 2010; Yelland *et al.*, 2010; Rahman *et al.*, 2011). Lockamy and McCormack (2009) conducted a study which uses Bayesian networks to examine operational risks in supply chains. The authors have also used these networks to analyze outsourcing risks in supply chains (Lockamy and McCormack, 2010). Finally, Lockamy (2011) has developed a methodology for benchmarking supplier risks using Bayesian networks.

This article builds on the aforementioned literature by introducing a methodology for modeling and evaluating risks in supply chains through the creation of supplier risk profiles using Bayesian networks. The networks are used to determine a supplier's external, operational and network risk probability, and the potential revenue impact a supplier can have on the organization as measured by VAR. The methodology is offered as a tool to assist managers in the creation of strategies and tactics designed to mollify overall supply chain risks.

4.2 Assessment model

This study employs a risk assessment model used to evaluate the risks of each supplier within the supply network. The model identifies and quantifies the risk of a supply disruption using a framework that describes key supplier attributes, along with their relationships and interactions with the company performing the assessment. The framework consists of the following risk factors: relationship factors, supplier past performance, human resources (HR) factors, history of supply chain disruptions, environmental factors, disaster history, and financial factors. The risk factors were developed based upon the literature illustrating approaches to supply chain risks cited in Section 3. Relationship factors include the level of influence, cooperation, power, and shared interests which exist within the network. Quality levels and on-time delivery history are key factors in assessing risks based on past performance. HR factors include employee relations issues, employee compensation as compared to industry norms, and unionization issues. The degree to which the supply chain has experienced disruptions is a key factor in assessing risks based upon its history. Additionally, the history of disaster events such as hurricanes, earthquakes, tornadoes, and floods are incorporated into the framework. Finally, funding sources, debt levels, cash flow analysis, and other indicators of financial health are utilized by the framework to assess financial risks. The risk assessment model is shown in Figure 1.

The model uses a set of measures and scales that apply to each risk construct. The measures were developed based upon key events which can directly impact a particular risk factor. The measures and scales are used to create supplier risk profiles. The profiles reflect the risk of a disruptive event involving a particular supplier. Supplier risk profiles are expressed as numerical scores ascertained as a result of applying the model and measures. The higher the risk profile score, the higher the disruption potential of the entity under review. In order to apply the risk results to potential events, the survey results were reorganized into operational, network and external risk-related measures, and the results were recalculated for each supplier. The reorganized measures are presented in Appendix 1. The revenue impact portion of the supplier risk profiles was calculated by: identifying the parts furnished by the supplier; mapping the parts to a finished product and gross revenue for that product; and, calculating the sum of associated monthly revenue for each supplier.

4.3 Sample and data collection

The data sample was a group of 15 automotive casting suppliers to a major automotive company in the USA. The data were collected using a four-step process. First, the suppliers' representatives were interviewed to discuss the study and the supplier

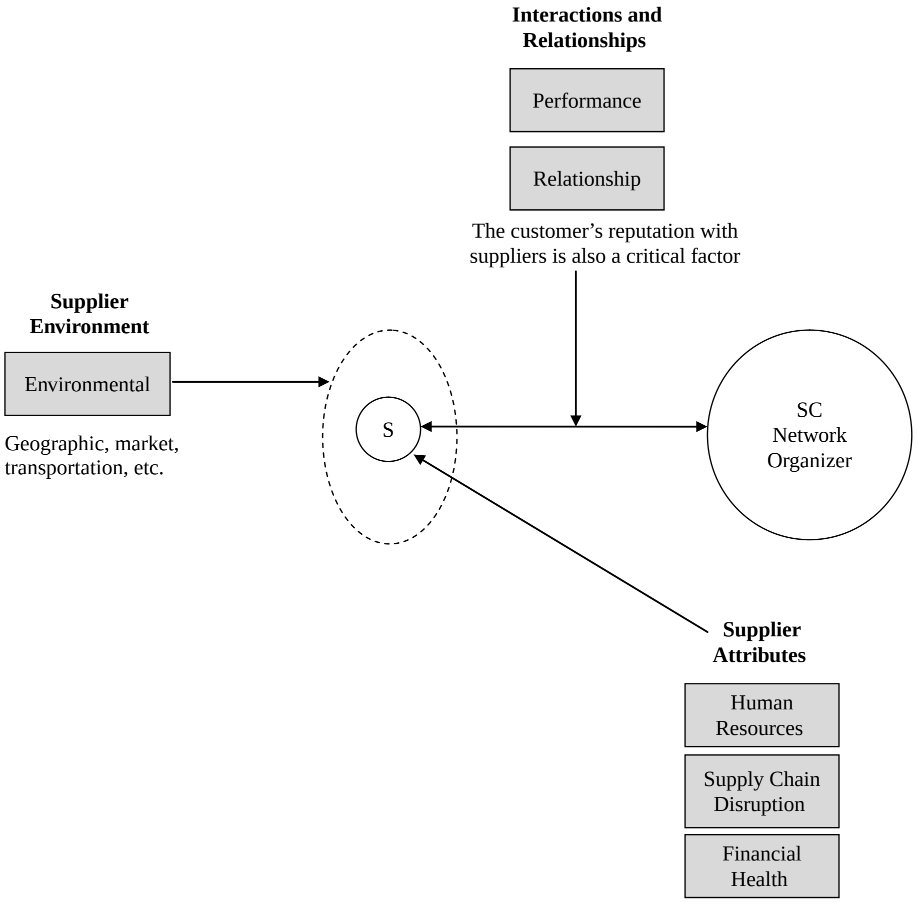


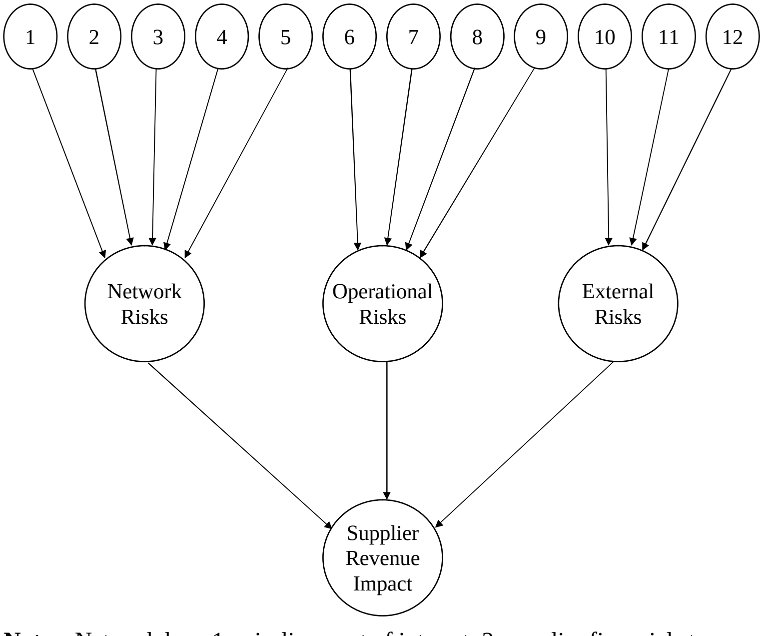
Figure 1.
Risk assessment model

self-assessment online survey instrument to be completed by the representatives. The survey instrument links were then sent by e-mail to the account representatives. Upon receiving the completed surveys, the next step was to conduct on-site interviews with key personnel in the supply chain departments to validate information collected via the survey instrument, and to obtain more specific details on their supply chain risk factors. The third step in the data collection process was to conduct interviews with commodity managers in the castings area in an effort to triangulate the data collected from the surveys and supply chain departments. Finally, off-site research was conducted to gather data regarding the following: market dynamics; mergers, divestitures, and acquisitions; regulatory issues; disasters; and transportation disruptions. This data were used to measure environmental risk factors. A five-point Likert scale was used for the rating of all risk factors, and a risk index was calculated for each supplier.

4.4 Research model

Bayesian networks were constructed to examine the probability of a supplier's impact on company revenues. Network, operational, and external risk levels were computed using the provided a priori probabilities for the identified risk events. These risk levels were then used to determine a supplier's probability of revenue impact on the company. A diagram of the Bayesian networks used in this study is shown in Figure 2.

Nodes (circles) represent variables in the Bayesian network. Each node contains states, or a set of probable values for each variable. The values "yes" and "no" represent the two states in which the variables can exist in the network shown in Figure 2. Nodes are connected to show causality with arrows known as "edges" which indicate the direction of influence. When two nodes are joined by an edge, the causal node is referred to as the parent of the influenced (child) node. Child nodes are conditionally dependent upon their parent nodes. Thus, in Figure 2, the probability of suppliers experiencing network risks is dependent on the a priori probabilities associated with the following variables: misalignment of interest; supplier financial stress; supplier leadership change; tier 2 stoppage; and supplier network misalignment. The a priori probabilities associated with the variables quality problems, delivery problems, service problems, and supplier HR problems directly influence operational risks. External risks are dependent upon the following variables: supplier locked (i.e. company cannot easily switch to another supplier), merger/divestitures, and disasters. The joint probabilities of the computed network, operational, and external risks are then used to determine the probability that a supplier will have an adverse impact on the company's revenue stream.



Notes: Network key: 1, misalignment of interest; 2, supplier financial stress; 3, supplier leadership change; 4, tier 2 stoppage; 5, supplier network misalignment; 6, quality problems; 7, delivery problems; 8, service problems; 9, supplier HR problems; 10, supplier locked; 11, merger/divestiture; 12, disasters

Figure 2.
Bayesian network for Supplier 1

5. Results

In this study, the product of the supplier's revenue impact probability times its revenue impact provides "VAR" dollars. VAR is defined as the minimum loss expected on a portfolio of assets over a certain holding period at a given probability (Venkataraman, 1997). For a given portfolio, probability and time horizon, VAR is expressed as a threshold value such that the probability that the mark-to-market loss on the portfolio over the given time horizon exceeds this value (assuming normal markets and no trading in the portfolio) is the given probability level (Jorion, 2006). Common parameters for VAR are 1 and 5 percent probabilities and one day and two-week horizons, although other combinations are in use (Pearson, 2002). VAR was developed by financial institutions in the early 1990s to provide senior management with a single number that could easily incorporate information on the risk of a portfolio of assets (Engle and Manganelli, 2004). Today, VAR has evolved into a risk measurement tool which can be applied outside of the financial management arena, such as in making procurement decisions (Sanders and Manfredo, 2002). VAR can also be used to evaluate and manage supply chain risks. The Supply Chain Council defines VAR as the sum of the probability of events times the monetary impact of the events for the specific process, supplier, product, or customer (SCOR Model version 9, 2008, p. 14). Thus, this metric allows for comparisons among suppliers to facilitate SCRM. This study examines monthly VAR dollars for the company based upon the risk profiles of each supplier.

The a priori probabilities for the 12 supply chain risk events which influence network, operational, and external risks are presented in Table I for each supplier. These values were used to generate a risk profile using Bayesian networks comprised of network, operational and external risk probabilities along with the supplier's probability of revenue impact on the company. The supplier risk profiles are displayed in Table II. The table reveals that Suppliers 1, 10 and 14 have the highest probability of revenue impact on the company, while Supplier 11 has the lowest probability of revenue impact. Computations illustrating the development of the risk profile for Supplier 1 and its associated VAR are presented in Appendices 2 and 3, respectively.

5.1 Risk reduction analysis

A risk profile reduction analysis was conducted for each supplier to determine the effects of minimizing various combinations of risk events (i.e. network, operational, and/or external risks have a zero probability of occurrence) on company revenues. While it may not be possible to reduce a risk event or category associated with a supplier's profile to a zero probability of occurrence, it may be possible to improve the profile by instituting proactive SCRM strategies and tactics in areas which will yield the maximum benefit. Thus, it is important for organizations to determine which risk categories, when improved, will provide the greatest risk reductions and benefits with respect to a particular supplier.

An illustration of risk reduction analysis for Supplier 1 is provided in Table III. The first row of values are network, operational, and external risk probabilities associated with Supplier 1 along with its probability of revenue impact, as illustrated in Table II. This is referred to as the base case. The subsequent rows illustrate the probability of revenue impact for Supplier 1 if it were possible to minimize a risk category (or a combination of risk categories) to the value of zero. The table shows that minimizing operational and external risk events reduces the probability of revenue impact from

Table I.
A priori probabilities for risk event variables

Supplier	Misalignment of interest	Supplier financial stress	Supplier leadership change	Tier 2 stoppage	Supplier network misalignment	Quality problems	Delivery problems	Service problems	Supplier HR problems	Supplier locked	Merger/ divestiture	Disasters
1	0.20	0.50	0.50	0.31	0.20	0.46	1.00	0.20	0.20	0.18	1.00	0.11
2	0.17	0.23	0.23	0.13	0.20	0.23	0.46	0.10	0.12	0.06	1.00	0.08
3	0.20	0.50	0.50	0.31	0.12	0.48	0.95	0.20	0.20	0.18	1.00	0.12
4	0.16	0.33	0.23	0.16	0.17	0.21	0.52	0.11	0.09	0.09	1.00	0.10
5	0.19	0.38	0.23	0.17	0.20	0.22	0.53	0.10	0.07	0.11	1.00	0.13
6	0.14	0.46	0.27	0.18	0.14	0.33	0.65	0.09	0.13	0.15	1.00	0.13
7	0.16	0.31	0.37	0.15	0.16	0.26	0.57	0.08	0.11	0.11	1.00	0.10
8	0.19	0.30	0.23	0.16	0.20	0.29	0.60	0.10	0.07	0.13	1.00	0.12
9	0.15	0.35	0.27	0.15	0.17	0.30	0.63	0.09	0.11	0.11	1.00	0.10
10	0.21	0.50	0.50	0.32	0.16	0.47	0.96	0.20	0.20	0.19	1.00	0.16
11	0.18	0.23	0.17	0.15	0.16	0.29	0.58	0.11	0.11	0.11	0.80	0.12
12	0.19	0.50	0.30	0.29	0.14	0.36	0.82	0.15	0.07	0.10	0.80	0.11
13	0.18	0.37	0.27	0.16	0.16	0.23	0.62	0.08	0.12	0.10	1.00	0.09
14	0.20	0.50	0.50	0.31	0.16	0.50	0.96	0.20	0.20	0.18	1.00	0.11
15	0.17	0.35	0.33	0.14	0.16	0.22	0.60	0.10	0.12	0.13	1.00	0.12

Supplier	Network risk probability	Operational risk probability	External risk probability	Probability of revenue impact
1	0.34	0.47	0.43	0.41
2	0.19	0.23	0.38	0.27
3	0.33	0.46	0.43	0.40
4	0.21	0.23	0.39	0.28
5	0.23	0.23	0.41	0.29
6	0.24	0.30	0.43	0.32
7	0.22	0.27	0.41	0.30
8	0.22	0.27	0.41	0.30
9	0.22	0.28	0.40	0.30
10	0.34	0.46	0.45	0.41
11	0.18	0.27	0.34	0.26
12	0.28	0.35	0.33	0.32
13	0.23	0.27	0.39	0.30
14	0.33	0.47	0.43	0.41
15	0.23	0.26	0.41	0.30

Table II.
Supplier risk profiles

Network risk probability	Operational risk probability	External risk probability	Probability of revenue impact
0.34[a]	0.47[a]	0.43[a]	0.41[a]
0.00	0.47	0.43	0.30
0.34	0.00	0.43	0.26
0.34	0.47	0.00	0.27
0.00	0.00	0.43	0.14
0.00	0.47	0.00	0.16
0.34	0.00	0.00	0.11

Note: [a]Base Case

Table III.
Risk profile reduction analysis for Supplier 1

the base case of 41-11 percent. A comparison of supplier risk profiles using a priori risk event probabilities and the most favorable risk profile reduction combinations of network, operational, and external risks (excluding the combination where all three risks categories have a zero probability of occurrence), along with corresponding VAR results are presented in Table IV. The first row of values corresponding to a given supplier represent its network, operational, and external risk probabilities along with its probability of revenue impact as displayed in Table II. This represents the base case risk profile for the supplier. Also included in these rows are the corresponding monthly revenue impacts for each supplier and VAR results for the base case. The subsequent rows illustrate the most favorable risk profile reduction combinations of network, operational, and external risks (excluding the combination where all three risks categories have a zero probability of occurrence), along with corresponding VAR results.

Upon examining Table IV, it is seen that the risk profile associated with Supplier 6 results in the largest VAR for the base case ($148.8 million) and the most favorable risk profile reduction combination ($37.2 million). The risk profile of Supplier 15 yields the smallest VAR for the base case ($2.12 million) and the most favorable risk profile reduction combination ($0.57 million). The largest percentage decrease in VAR between

Supplier	Network risk probability	Operational risk probability	External risk probability	Probability of revenue impact	Monthly revenue impact (millions)	Value-at-risk (probability × monthly revenue impact)	VAR reduction percentage
1	0.34[a]	0.47[a]	0.43[a]	0.41	$18.75	$7,687,500	73.2
	0.34	0.00	0.00	0.11	$18.75	$2,062,500	
2	0.19[a]	0.23[a]	0.38[a]	0.27	$31.25	$8,437,500	77.8
	0.19	0.00	0.00	0.06	$31.25	$1,875,000	
3	0.33[a]	0.46[a]	0.43[a]	0.40	$217.5	$87,000,000	72.5
	0.33	0.00	0.00	0.11	$217.5	$23,925,000	
4	0.21[a]	0.23[a]	0.39[a]	0.28	$180.42	$50,516,667	75.0
	0.21	0.00	0.00	0.07	$180.42	$12,629,400	
5	0.23[a]	0.23[a]	0.41[a]	0.29	$75.00	$21,750,000	79.3
	0.00	0.23	0.00	0.06	$75.00	$ 4,500,000	
6	0.24[a]	0.30[a]	0.43[a]	0.32	$465.00	$148,800,000	75.0
	0.24	0.00	0.00	0.08	$465.00	$ 37,200,000	
7	0.23[a]	0.26[a]	0.40[a]	0.29	$89.58	$25,979,167	72.4
	0.00	0.26	0.00	0.08	$89.58	$ 7,166,400	
	0.23	0.00	0.00	0.08	$89.58	$ 7,166,400	
8	0.22[a]	0.27[a]	0.41[a]	0.30	$17.50	$5,250,000	76.8
	0.22	0.00	0.00	0.07	$17.50	$1,225,000	
9	0.22[a]	0.28[a]	0.40[a]	0.30	$290.83	$87,249,000	76.7
	0.22	0.00	0.00	0.07	$290.83	$20,358,100	
10	0.34[a]	0.46[a]	0.45[a]	0.41	$136.25	$55,862,500	73.2
	0.34	0.00	0.00	0.11	$136.25	$14,987,500	
11	0.18[a]	0.27[a]	0.34[a]	0.26	$45.83	$11,915,800	76.9
	0.18	0.00	0.00	0.06	$45.83	$ 2,749,800	
12	0.28[a]	0.35[a]	0.33[a]	0.32	$45.83	$14,665,600	71.9
	0.28	0.00	0.00	0.09	$45.83	$ 4,124,700	
13	0.23[a]	0.27[a]	0.39[a]	0.30	$94.58	$28,374,000	73.3
	0.23	0.00	0.00	0.08	$94.58	$ 7,566,400	
14	0.33[a]	0.47[a]	0.43[a]	0.41	$20.83	$8,540,300	73.2
	0.33	0.00	0.00	0.11	$20.83	$2,291,300	
15	0.23[a]	0.26[a]	0.41[a]	0.30	$7.08	$2,124,000	73.3
	0.23	0.00	0.00	0.08	$7.08	$ 566,400	

Note: [a]Base case

Table IV.
Risk profiles and VAR reduction analysis

a supplier's base case and most favorable risk profile reduction combination is 79.3 percent for Supplier 5 ($21.7 million versus $4.5 million). In addition, the average percentage decrease in VAR between the base case and most favorable risk profile reduction combination is 74.7 percent for all suppliers. Along with Supplier 5, Suppliers 2, 11, 8, and 9 exhibited the largest VAR decreases between their base case and most favorable risk combinations (77.8, 76.9, 76.8, and 76.7 percent, respectively). The smallest percentage decrease in VAR between the two risk profiles was 71.9 percent, as exhibited by Supplier 12. The most prevalent risk reduction combination that offers the greatest potential for VAR improvement is the simultaneous minimization of operational and external risk events. This combination resulted in the lowest probability of revenue impact for 14 suppliers. The network risk-external risk reduction combination provided the lowest probability of revenue impact for two suppliers.

For Supplier 7, both the network risk-external risk and operational risk-external risk reduction combinations yielded the lowest probability of revenue impact and corresponding VAR values. The simultaneous minimization of network and operational risk events failed to yield a most favorable risk combination for any supplier.

6. Managerial actions

As illustrated in Table IV, Supplier 6 has the potential to have the largest negative impact on company revenues. Therefore, proactive measures should be taken by the company to reduce its VAR exposure with this supplier. Efforts should be made to aid the supplier in reducing the probability of operational and external risk events as part of an overall SCRM strategy. For example, in the area of operational risk, Supplier 6 estimates a 65 percent probability of a delivery problem occurrence as seen in Table I. Supply chain risk mitigation tactics should be applied in this area to reduce the potential impact of this event. Faisal *et al.* (2006b) have identified 11 enablers of risk mitigation in supply chains: information sharing; supply chain agility; trust among supply chain partners; collaboration relationships among supply chain partners; information security; corporate social responsibility; aligned supply chain incentives and revenue sharing policies; supply chain risk planning; supply chain risk sharing; supply chain risk knowledge; and continual risk analysis and assessment. If the company plans to maintain Supplier 6 as a part of its network, then it should institute strategies, tactics, and measures in these risk mitigation areas to address potential delivery problems and other operational and external risk events exhibiting a high probability of occurrence. Contrarily, the company may choose to terminate its relationship with this supplier, or allocate more of its business to a supplier with a less risky profile.

Table IV also shows that one-third of the suppliers have the potential to reduce their VAR impact on the company by at least 77 percent through the minimization of network, operational, and external risk events. Moreover, company VAR exposure can potentially be reduced by an average of 75 percent for the supplier network, resulting in a $1,302.2 million reduction in VAR. Given the magnitude of these dollars, the company should develop and implement an aggressive SCRM program which moves the organization towards the realization of these reductions. The company, along with its supply chain partners, should work towards minimizing the probability of risk events that have the largest VAR impact and highest chance of occurrence. The risk mitigation enablers outlined previously could be used as the basis for the creation of a shared SCRM program among network partners designed to govern overall SCRM practices.

7. Conclusions

The methodology used in this study can be adopted by managers to formulate SCRM strategies and tactics which mitigate overall supply chain risks. Bayesian networks can be used to develop supplier risk profiles to determine the risk exposure of a company's revenue stream for its supplier base. Based on these profiles, organizations can determine if it is in their best interest to either assist a supplier in improving their risk profile, or altering their relationship. The supplier risk profiles can be used to determine those risk events which have the largest potential impact on an organization's revenues, and the highest probability of occurrence. As part of a comprehensive supplier risk management program, organizations along with their suppliers can develop targeted approaches to minimize the occurrence of these risk events.

This methodology can also be used as a means of monitoring risk in the supply network. Suppliers could be required to provide periodic updates of the probability of occurrence for the risk events outlined in Appendix 1. These updates could be incorporated into a Bayesian network to create a new risk profile for each supplier. Risk management strategies, policies, and tactics could then be adjusted to reflect the new risk realities associated with the supply network. Thus, the methodology provides a proactive means of managing supply chain risks.

Finally, the use of Bayesian networks to model supply chain risks can be used as a tool to assist managers in determining a supplier's status in the supply network. For example, suppliers who have been shown to improve their risk profiles over time may be rewarded by an organization via the apportionment of more business. On the contrary, suppliers who have experienced increases in network, operational, and/or external risk events over time may be classified as "at risk" suppliers whose relationship may be subject to alteration. Ultimately, the alteration could result in removal from the supply network. This tool could not only be used to evaluate current suppliers, but also to examine the viability of potential suppliers based upon the generation of their risk profiles using Bayesian networks.

8. Limitations

This study focused on the risk profiles associated with a group of casting suppliers in the automotive industry. Thus, the results could be industry-specific. A limitation to the use of Bayesian networks to model supply chain risks is the proper identification of risk event and risk categories that can impact a supply chain. As demonstrated by the literature review, there are a variety of approaches available for categorizing supply chain risks. The inability to incorporate all relevant risks into the model could limit its effectiveness in representing a supplier's true risk profile. A potential data limitation is access to supplier risk event probabilities, which are essential to the construction of the Bayesian networks. Moreover, the data must be a reliable estimate of the supplier's beliefs regarding the occurrence of these risk events. Unwillingness by suppliers to either provide such information, or to update it to represent current risk realities can limit the usefulness of the model. Finally, the impact of supply chain structure on supply risks was not addressed in the study.

9. Future research

Studies which examine supplier risk profiles and supply networks using Bayesian networks should be conducted to determine if supply chain risks are significantly influenced by industry dynamics. Future researchers may choose to explore how this methodology could be used to assist managers in making outsourcing decisions based upon supplier risk profiles. Finally, the effects of simultaneous reductions in network and operational risk events may be examined by future researchers to determine if there are supply networks and/or industries where this combination results in the most favorable risk reduction combination as measured by VAR dollars.

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Appendix 1

Table AI.
Network, operational and external risk measures

Risk category	Risk event	Risk measures
Network risks	Misalignment of interest	
		Influence of revenue from company
		Supplier revenue from commodity category
		Supplier/company alignment
		Regulatory
	Supplier financial stress	
		Customer portfolio
		Business health indicators
		Segment portfolio
		Market growth
		Financial data sharing
	Supplier leadership change	
		Company ownership change likelihood
		Merger and acquisition
		Senior staff turnover
	Tier 2 stoppage	
		Process change likelihood
		Miscommunication between tiers
		Material change/obsolesce likelihood
		Risk management system
		Material sourcing base
		Market power
		Regulatory
		Regulatory change risk likelihood
		Inventory status sharing
		Tier 2 supplier information sharing
		Process/material change notification
	Supplier network misalignment	
		Supplier customer alignment
		Vendor concentration
Operational risks	Quality problem	
		Process change likelihood

(*continued*)

Risk category	Risk event	Risk measures
		MRR (defects) Audit date Audit score Tier 2 performance monitoring Quality problems likelihood Manufacturing employees Accreditation Material change/obsolesce likelihood Process/material change notification
	Delivery problem	Performance data sharing On-time delivery Capacity utilization Tier II information sharing Delivery flexibility Capacity shortage likelihood Manufacturing employees Capacity change Inventory status sharing Order fulfillment information sharing Production schedule sharing
	Service problem	Engineering support Service promptness Employee turnover HR issues likelihood New technology opportunity sharing
	Supplier HR problem	Union issues Employee turnover Pay position
External risks	Supplier locked	Accreditation information sharing EPA and FDA report sharing Regulatory Accreditation
	Merger/divestiture	Market dynamics Merger and acquisition
	Disasters	Supplier is providing proof of insurance Disaster Transportation

Table AI.

Appendix 2. Risk profile for Supplier 1

Given the risk event relationships exhibited in the Supplier Bayesian Network shown in Figure 2 along with the a priori probabilities for risk event variables contained in Table I, the following probability computations regarding network risks, operational risks, external risks, and revenue impact for Supplier 1 are provided below:

$$P(\text{Network risks}) = \frac{\Sigma(\text{Probability of network risk event}) \times (\text{Probability of event occurrence})}{\Sigma(\text{Probability of event occurrence})}$$

$$P(\text{Network risks}) = \frac{[(0.20) \times (1)] + [(0.50) \times (1)] + [(0.50) \times (1)] + [(0.31) \times (1)] + [(0.20) \times (1)]}{1 + 1 + 1 + 1 + 1}$$

$$P(\text{Network risks}) = \frac{1.71}{5} = 0.34$$

$$P(\text{Operational risks}) = \frac{\Sigma(\text{Probability of operational risk event}) \times (\text{Probability of event occurrence})}{\Sigma(\text{Probability of event occurrence})}$$

$$P(\text{Operational risks}) = \frac{[(0.46) \times (1)] + [(1.00) \times (1)] + [(0.20) \times (1)] + [(0.20) \times (1)]}{1 + 1 + 1 + 1}$$

$$P(\text{Operational risks}) = \frac{1.86}{4} = 0.47$$

$$P(\text{External risks}) = \frac{\Sigma(\text{Probability of external risk event}) \times (\text{Probability of event occurrence})}{\Sigma(\text{Probability of event occurrence})}$$

$$P(\text{External risks}) = \frac{[(0.18) \times (1)] + [(1.00) \times (1)] + [(0.11) \times (1)]}{1 + 1 + 1}$$

$$P(\text{External risks}) = \frac{1.29}{3} = 0.43$$

$$P(\text{Revenue impact}) = \frac{\Sigma[P(NR) \times P(\text{Occurrence})] + [P(OR) \times P(\text{Occurrence})] + [P(ER) \times P(\text{Occurrence})]}{\Sigma(\text{Probability of risk occurrence})}$$

$$P(\text{Revenue Impact}) = \frac{[(0.34) \times (1)] + [(0.47) \times (1)] + [(0.43) \times (1)]}{1 + 1 + 1}$$

$$P(\text{Revenue impact}) = \frac{1.24}{3} = 0.41$$

Appendix 3. VAR for Supplier 1

Given the risk profile exhibited in Appendix 4, the following VAR computation for Supplier 1 is provided below:

$$\text{Value at risk (VAR)} = [P(\text{Revenue impact})] \times [\text{Supplier's monthly revenue impact}]$$

From Appendix 4: P(Revenue impact) = 0.41.

Using the methodology described in Section 3.2, the monthly revenue impact for Supplier 1 is: $18,750,000.

Therefore: VAR(Supplier 1) = [0.41] × [$18,750,000] = $7,687,500.

Thus, the risk profile associated with Supplier 1 results in a VAR of $7,687,500 for the automotive company.

About the authors

Dr Archie Lockamy III, PhD, CFPIM is the Margaret Gage Bush Professor of Business and Professor of Operations Management at Samford University. Prior to his academic career, Dr Lockamy held various engineering and managerial positions with Du Pont, Procter and Gamble, and TRW. He has published research articles in numerous academic journals, and co-authored the book *Reengineering Performance Measurement: How to Align Systems to Improve Processes, Products and Profits*. He served on the 1997, 1998, 1999, 2000, 2001, and 2002 Board of Examiners for the Malcolm Baldrige National Quality Award via appointment by the US Department of Commerce. He also served as Vice President of the Board of Directors of the American Production and Inventory Control Society (APICS) Educational and Research Foundation. Dr Lockamy is recognized as a Certified Fellow in Production and Inventory Management (CFPIM) by APICS, and is certified as an Academic Jonah by the Avraham Y. Goldratt Institute. Dr Archie Lockamy III is the corresponding author and can be contacted at: aalockam@samford.edu

Dr Kevin McCormack has over 25 years of business leadership and consulting experience in the areas of strategy, operations, business planning, business process engineering, re-engineering, change management, supply chain management, organizational design, and information technology implementation. His experience covers many national and international business segments and a broad range of business processes. He is the author of several articles that have appeared in academic and professional journals, and has authored five books in the area of business process orientation.