Expert Systems With Applications xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Expert Systems With Applications

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

A software application for rapid risk assessment in integrated supply chains

Q1 Faisal Aqlan*

Department of Industrial Engineering, Pennsylvania State University, The Behrend College, Erie, PA 16563, United States

ARTICLE INFO

Keywords:
Rapid risk assessment
Probability theory
Fuzzy logic
Risk priority matrix
Integrated supply chains

ABSTRACT

Supply chain risk management (SCRM) has become a critical component of supply chain management with the movement to global supply chains and the increasing occurrence of internal and external risk events. Effective management of supply chain risks requires a comprehensive yet rapid assessment of all the risk factors in the supply chain and their potential impacts. This paper presents a software application framework for rapid risk assessment (RRA) in integrated supply chains. The proposed framework combines qualitative and quantitative methods to assess and prioritize the risks. Qualitative methods are based on surveys used to collect the risk probability and impact data for the main agents in the supply chain (*i.e.*, supplier, customer, manufacturer, etc.). Quantitative methods are based on probability theory and fuzzy logic. Risks are calculated for each agent in the supply chain and are then aggregated per product type. The proposed RRA tool was tested in a manufacturing environment to assess the validity of the proposed framework. Results from the case study showed that the assessment obtained by the proposed framework agrees with what the risk management experts think about the risk levels and priorities in the company.

1. Introduction

Supply chain management can be defined as "the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole" (Christopher, 2011). The goal of supply chain management is to manage the relations among supply chain components in order to achieve more profitable outcomes for all supply chain parties. Supply chain performance may be negatively impacted by of the occurrence of risk events in different stages of the supply chain system. The management of such events is known as supply chain risk management (SCRM), which has become a critical part of the organizational strategy. SCRM has gained more attention with the movement to global supply chains and the increasing number of disruptions that affect the performance of supply chains. SCRM focuses on the identification of potential risks and disruptions in the supply chain and developing mitigation strategies to reduce the impact of these disruptions and risks on supply chains.

An essential step for risk management is the understanding of the different categories of risks, and the events and conditions that drive these risks. The goal of SCRM is to prepare the company to be able to respond to different types of risks in such a way that minimizes the impact on its operations. The art of risk management is to "identify risks specific to an organization and to respond to them in an appropriate way" (Merna & Al-Thani, 2005). For risk management to be effective, all different levels of the organization need to be considered. According to Blackhurst and Wu (2009), most of the definitions of SCRM include the following activities: (1) Risk identification and modeling (2) Risk analysis, assessment and impact measurement (3) Risk management (4) Risk monitoring and evaluation (5) Organizational and personal learning including knowledge transfer. Like other management approaches, SCRM requires good quality of knowledge, abilities, experiences, and skills. It ensures that the principles established by managers are applied to logistics' risk (Waters, 2007).

Risk events represent a daily challenge to supply chain and logistics management. The ability to respond to and mitigate these risk events puts the company ahead of its competitors and reduces the expected long-term damage to its business. Risk exists in supply chain because of the uncertainty about future risk events, which can appear at any time point in the supply chain. Risks in the supply chain can be classified into five types: demand risk, supply risk, process risk, planning and control risk, and environmental risk. These five types of risks can be further classified into: internal to the organization (process risk and planning and control risk), external to the organization but internal to the supply chain (demand risk and supply risk), and external to the supply chain (environmental risk). To manage the risks and minimize their impact on the organization, risk mitigation strategies are implemented. The selection of risk mitigation strategies

* Tel.: +1 814 898 6945.
E-mail address: fua11@psu.edu

http://dx.doi.org/10.1016/j.eswa.2015.08.028
0957-4174/

depends on risk type and organization's budget. Chopra and Sodhi (2004) listed the following risk mitigation strategies: adding capacity, adding inventory, having redundant suppliers, increasing responsiveness, increasing flexibility, aggregating or pooling the demand, increasing capability, and having more customer accounts.

Effective management of supply chain risks requires a comprehensive yet rapid assessment of all of the risk factors in the supply chain and their potential impacts. Quantitative risk assessment models have been proved to be an effective and efficient methodology for quantitatively evaluating risks in supply chains. Risk management software that implements quantitative models for risk assessment is also available. However, most of these software tools are commercial and they do not consider the different aspects of supply chain risks.

The paper is structured as follows. Section 2 discusses the literature related to risk assessment in integrated supply chains. In Section 3 a conceptual framework for rapid risk assessment in integrated supply chains is laid out, characterizing the main types of risk that are encountered by participants within those supply chains, and characterizing the range of measures that can be taken to manage such risks. Section 4 discusses the proposed software application. A detailed description of the software main components is provided. Section 5 presents a case study from a real manufacturing integrated supply chain. Finally, conclusions and future work are discussed in Section 6.

2. Related literature

The management of supply chain risks has received more attention with the increase in the number of risk events such as international terrorism, economic crises, and wars (Lim, 2010; Sheffi, 2002). Different frameworks for supply chain risk management and mitigation have been proposed in the literature. For example, a framework that considers the effects of risk sharing and information management in supply chain networks was developed by Wakolbinger and Cruz (2011). Diabat, Govindan, and Panicker (2012), discussed the analysis and mitigation of risks in a food supply chain. Chen, Sohal, and Prajogo (2013) developed a collaborative approach for mitigation operational risks in supply chains including: supply risks, demand risks, and process risks. A framework for product quality risk and visibility assessment was presented by Tse and Tan (2011). The study argues that better visibility of risk in supply tiers could minimize quality risks. One main limitation of the literature on supply chain risks is that the most studies do not consider risk factors and risk interconnections when risks are calculated and assessed.

Many researches utilized qualitative and quantitative techniques to study supply chain risks. Wu, Blackhurst, and Chidambaram (2006) developed a quantitative model for inbound supply risk analysis based on Analytic Hierarchy Process (AHP). The study also built a prototype computer implementation system and tested it using an industry example. A framework for modeling and analyzing supply chain risks based on timed Petri nets was proposed by Alpan and Gonca (2010). An optimization model for finding the optimal number of suppliers under the risk of supply disruption was developed by Sarkar and Mohapatra (2009). Goh, Lim, and Meng (2007), proposed a stochastic model for managing risks in global supply chains including: demand, supply, disruption, and exchange risks. Simulation modeling has also been used to study and analyze supply chain risks. Schmitt (2009) discussed the use of discrete-event and Monte Carlo simulation methods to quantify supply chain disruption risks.

Uncertainty in supply chain risk assessment causes the decision making to be a complex process. Risks occur in supply chains because of uncertainty about the future (Waters, 2007). Reduction of uncertainty in managing supply chain risks has an economic value and it improves the accuracy of risk management decisions. According to Bogataj and Bogataj (2007), uncertainty level depends on the type and amount of information that is available to estimate the risk likelihood and its impact. In order to reduce the uncertainty in supply chain risks, fuzzy set theory, probability theory, and knowledge management principles can be utilized**.** The use of fuzzy logic methods for risk identification and modeling in supply chains was presented in Ebrahimnejad, Mousavi, and Seyrafianpour (2010). A fuzzy multicriterion model for the assessment of suppliers in supply chains was developed by Hamidi (2011). Aqlan and Ali (2014), combined Lean principles with fuzzy logic for risk assessment in chemical industry. An integrated framework for supply chain risk assessment based on fuzzy logic was proposed in Aqlan and Lam (2015a).

Software tools for risk management have been discussed in the literature. For example, Fugini, Teimourikia, and Hadjichristofi (2015) presented a web-based cooperative tool for risk management with adaptive security utilizing event-condition-action meta-rules. Stornetta, Engeli, Zarn, Gremaud, and Sturla (2015) developed a risk management tool to prioritize chemical hazard-food pairs. The tool is based on the derivation of a "Priority Index" (PI) that is based on the ratio of the potency of the hazard and the consumer exposure. Hochrainer-Stigler, Mechler, and Mochizuki (2015) presented a risk management tool for tackling country-wide contingent disasters. One major limitation of the literature on supply chain risk management is the lack of rapid and comprehensive assessment methods to quantify and assess the risks. In addition, most of the available commercial softwares for supply chain management do not provide a comprehensive quantitative assessment of the risks. They may also require a long time to perform the risk assessment process.

This study proposes a framework and a software implementation for a comprehensive assessment of risks in the integrated supply chains. The proposed framework considers the factors that cause the risks of the different agents in the supply chain (i.e., suppliers, customers, manufacturers, etc.).

3. Rapid risk assessment framework

The proposed methodology for Rapid Risk Assessment (RRA) is shown in Fig. 1. The proposed framework integrates both qualitative and quantitative risk assessment methods. Qualitative risk assessment is based on survives and interviews while quantitative analysis uses probability theory and fuzzy logic. The quantitative part of the framework provides a new approach for risk assessment in integrated supply chains. The RRA framework starts with identifying the main agents in the supply chain (i.e., suppliers, manufacturers, distributers, customers, etc.) and their interactions. The type and number of agents are based on the structure of the integrated supply chain. Once the agents of the supply chain and the interaction among them are identified, risk factors are determined for each agent. Risk factors data is collected through surveys distributed to the risk management experts. More risk factors data can also be collected based on historical (and current) data and using simulation techniques. For each agent in the supply chain, risk factor data are collected for probability and impact of the risk and the current mitigation strategies. The collected data for the risk factors is used to calculate the aggregated risk values for the agents. Risk Priority Matrix (RPM) is used to calculate the risk per risk type and per each agent in the supply chain. Based on the bill of the materials (BOM) for product and the supply chain agents involved in producing the product and delivering it to the customer, risk is aggregated per product. This allows for comparing the risks associated with the different product types in the integrated supply chain. The following sections discuss the steps of the RRA framework in detail.

3.1. Identify main agents in the supply chain and their interactions

The main agents in the supply chain and the interaction among them can be identified using on the Supply Chain Operations Reference (SCOR) model. The SCOR model is a framework for evaluating

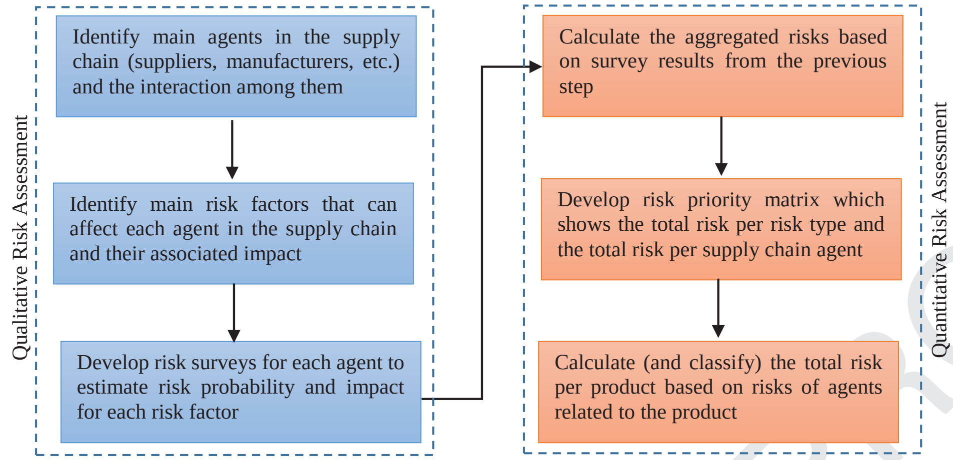

Fig. 1. Rapid risk assessment framework for integrated supply chains.

Fig. 2. An illustration of SCOR model.

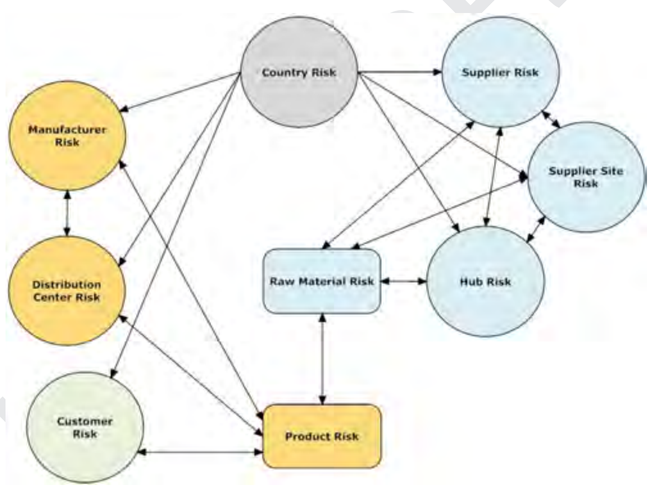

Fig. 3. Risk interactions among supply chain agents (Aqlan & Lam, 2015a).

supply chain activities and their performance. It views the supply chain activities as a series of interlocking inter-organizational processes. An illustration of the SCOR model is shown in Fig. 2. The model provides a unique framework that links performance metrics, processes, best practices, and people into a unified structure. The model is used for rapid assessment of supply chain performance.

To identify the interactions among the different agents in the integrated supply chain, risk flow analysis is performed (Aqlan & Lam, 2015a). Fig. 3 shows the interactions among the main components of the supply chain. Risk can flow from country (or environment) to suppliers, manufacturers, and customers. Raw material risk is affected by the supplier risk. The product risk is affected by the manufacturer risk, customer risk, and raw material risk.

3.2. Identify main risk factors

Risk factors are dynamic, they change over time. For this reason, companies should have continuous assessment risk management programs to identify the risk factors that can affect the supply chain operations. The direct risks that could affect the supply chain performance and the correlation among these risks are identified by the supply chain experts. For each risk, the main factors or root causes should also be identified. The risk factor data is collected through surveys and interviews with experts. An example of the identified direct risk factors for a manufacturing site is shown in Fig. 4.

3.3. Develop risk surveys for each agent

Once the risks and their associated factors are identified, a survey is developed and distributed to the supply chain risk experts to estimate the risk factor parameters including probability of occurrence and impact. The estimated values are then used as inputs for risk calculations. The first step of designing the survey is to choose the respondents, which are the persons who will estimate the probability, impact, and other risk parameters. For each risk factor, the respondent is asked to give an estimate for the probability of occurrence of the risk factor and its impact (values between 0 and 1). An example of a survey for the manufacturing site is shown in Table 1.

Fig. 4. An example of risk factors for a manufacturing site.

Table 1
Risk factor survey for the manufacturing site.

Factor code	Risk factor question	Likelihood	Resulting impact
QLTY	How likely the company will have severe quality problems?		
INRY	How likely the inventory will run out and affect production?		
CAPS	Will the company have capacity shortage that will affect production?		
NPDI	How likely the company will have new product introduction issues?		
INOV	How likely the company will have innovation issues?		
OCUP	How likely the occupational risk will occur in the workplace and affect workers and production?		

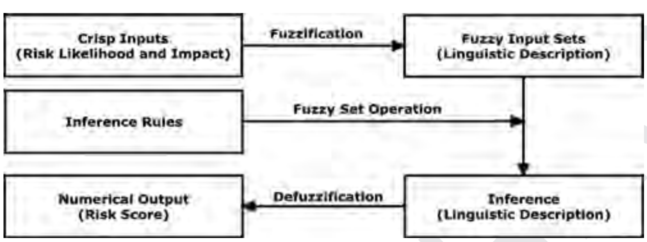

Fig. 5. An illustration of the fuzzy logic system.

3.4. Calculate aggregated risks

In order to calculate the risk values, the risk factors' probability and impact data needs collected from the surveys. Once the data is collected, the aggregated risk value is calculated based on the values of the associated risk factors' likelihood and impact. Assuming that the risk factors are independent and the occurrence of any of the risk factors will cause the risk event to occur, the following equation is used to aggregate the risk likelihood:

$$P_n = 1 - \prod_{i=1}^{M} (1 - p_i) \qquad (1)$$

where P_n is the aggregated probability of occurrence of risk for agent n and p_i is the probability of occurrence of risk factor i. M is the number of risk factors associated with the risk agent n (for example, in Fig. 4, $M = 6$). The aggregated impact of the risk is then calculates as:

$$L_n = \frac{\sum_{i=1}^{M} p_i \times L_i}{\sum_{i=1}^{M} p_i} \qquad (2)$$

where L_n is the aggregated likelihood of the risk for agent n and l_i is the resulting impact factor i. M is the number of risk factors associated with the agent n. The two aggregated parameters, risk likelihood and impact, are used to calculate the risk score for the agent using the fuzzy inference system. An illustration of the fuzzy inference system is shown in Fig. 5. The membership function for the linguistic variables of the risk likelihood is shown in Fig. 6. The fuzzy inference rules are represented by the surface plot shown in Fig. 7.

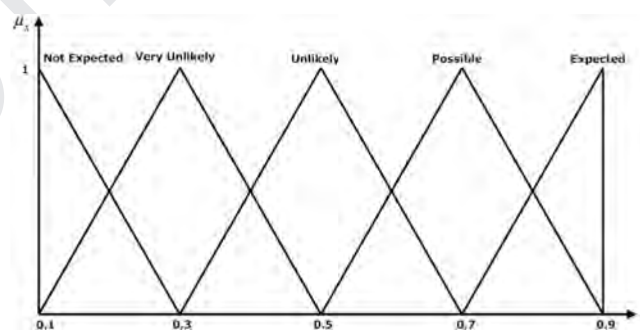

Fig. 6. Membership function of the likelihood linguistic variables.

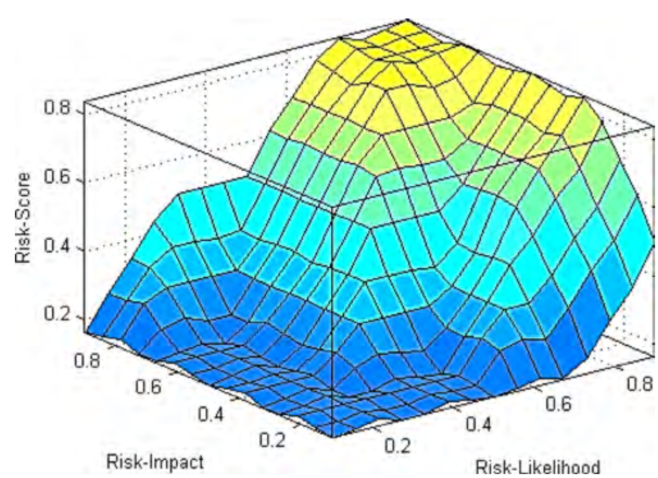

Fig. 7. Surface plot for the fuzzy inference rules.

3.5. Develop risk priority matrix

To assess the total risk for each agent of the supply chain, risk priority matrix is proposed (see Table 2). Risk priority matrix is used to calculate the overall risk for each supply chain agent and the overall

Please cite this article as: F. Aqlan, A software application for rapid risk assessment in integrated supply chains, Expert Systems With Applications (2015), http://dx.doi.org/10.1016/j.eswa.2015.08.028

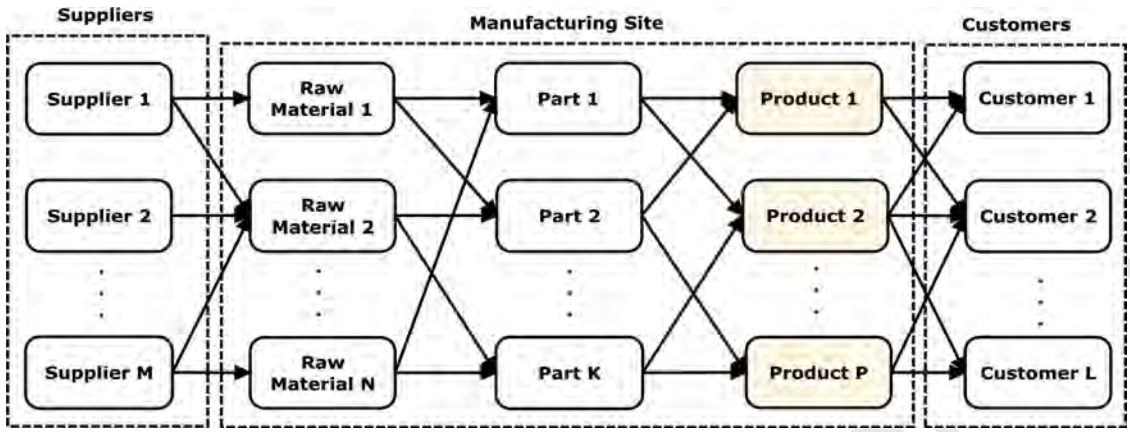

Fig. 8. Risk aggregation per product.

Table 2
Risk priority matrix.

Supply chain agent	Risk 1	Risk 2	Risk 3	...	Risk M	Agent risk
Agent 1	R_{11}	R_{21}	R_{21}	...	R_{M1}	RA_1
Agent 2	R_{12}	R_{22}	R_{32}	...	R_{M2}	RA_2
Agent 3	R_{13}	R_{23}	R_{33}	...	R_{M3}	RA_3
.	.	.	.	.	.	.
.	.	.	.	.	.	.
Agent N	R_{1N}	R_{2N}	R_{3N}	...	R_{MN}	RA_N
Total risk	RS_1	RS_1	RS_1	...	RS_M	**PRODUCT RISK**

score for each risk type. To calculate the total risk per agent and the total risk, the following equations are used:

$$RA_i = \varphi\left(1-\prod_{j=1}^{M}\left(1-p_j\right),\ \frac{\sum_{j=1}^{M} p_j L_j}{\sum_{j=1}^{M} p_j}\right), \quad i = 1, 2, 3, \ldots, N \tag{3}$$

$$RS_j = \varphi\left(1-\prod_{i=1}^{N}\left(1-p_i\right),\ \frac{\sum_{i=1}^{N} p_i L_i}{\sum_{i=1}^{MN} p_i}\right), \quad j = 1, 2, 3, \ldots, M \tag{4}$$

where φ is the function used by the fuzzy inference system to calculate final crisp values for the risks based on the aggregated probability and impact of the supply chain. N is the number of agents in the integrated supply chain and M is the number of risk types. The agents of and the different types of risks are then prioritized based on the risk values in the risk priority matrix.

3.6. Calculating total risk per product

The last step in the proposed framework is risk calculation and classification per product type. The risks calculated in Step 5 for each agent are used to calculate the total aggregated risk for the product type based on bill-of-material (BOM) and supply chain structure. An example of how risk is calculated per product type is shown in Fig. 8.

The product risk is a combination of customer's risk, part's risk, and manufacturing site's risk. Part risk is calculated based on the risk of the raw material associated with the part. Raw material risk is calculated based on the risk of the supplier who provides the raw materials. Assuming the parameters for suppler i risk ($i = 1, 2, \ldots, M$), R_i^s, are: $P_i^s$and L_i^s, the risk parameters for the raw material j (j = 1,2,..., N) is calculated as:

$$P_j^w = 1-\prod_{i=1}^{M}\left(1-\varepsilon_{ij}P_i^s\right), \quad \text{j} = 1, 2, \ldots, \text{N} \tag{5}$$

$$L_j^w = \frac{\sum_{i=1}^{M} \varepsilon_{ij} L_i^s P_i^s}{\sum_{i=1}^{M} \varepsilon_{ij} P_i^s}, \quad \text{j} = 1, 2, \ldots, \text{N} \tag{6}$$

where R_i^s is the risk associated with supplier i and the value this risk is calculated by the fuzzy inference system based on the risk likelihood, P_i^s, and impact L_i^s. P_j^w and L_j^w are the risk parameters, likelihood and impact, associated with the raw material j. ε_{ij} is a binary variable that takes the value of 1 if supplier i is a provider of raw material j and 0 otherwise. Similarly, the part risk, R_k^p, is calculated based on the risk of the raw materials associated with that part. Product risk is also calculated the same way based on part's risk, customer's risk, and manufacturing site's risk. Let the customer's risk parameters are P_l^C and $L_l^C (l = 1, 2, \ldots, L)$, the manufacturing site's risk parameters are P_q^o and L_q^o ($q = 1, 2, \ldots, Q$), and the part's risk parameters are P_k^t and $L_k^t (k = 1, 2, \ldots, K)$, the aggregated risk parameters for the product are calculated as:

$$P^r = 1-\left[1-\prod_{l=1}^{L}\left(1-\varepsilon_{pl}P_l^c\right)\right]\left[1-\prod_{q=1}^{Q}\left(1-\varepsilon_{pq}P_q^o\right)\right] \times \left[1-\prod_{k=1}^{K}\left(1-\varepsilon_{pk}P_k^t\right)\right] \tag{7}$$

$$L^r = \frac{\sum_{l=1}^{L} \varepsilon_{pl} L_l^c P_l^c + \sum_{q=1}^{Q} \varepsilon_{pq} L_q^o P_q^o + \sum_{k=1}^{K} \varepsilon_{pk} L_k^t P_k^t}{\sum_{l=1}^{L} \varepsilon_{pl} P_l^c + \sum_{q=1}^{Q} \varepsilon_{pq} P_q^o + \sum_{k=1}^{K} \varepsilon_{pk} P_k^t} \tag{8}$$

4. RRA software application

The rapid risk assessment (*RRA*) software tool was developed based on the proposed framework. An illustration of the structure of the software tool is shown is Fig. 9. The RRA tool combines qualitative and quantitative techniques for the assessment and calculation of the risks in integrated supply chains. The tool consists of five main modules: agent identification, risk identification, agent survey, risk

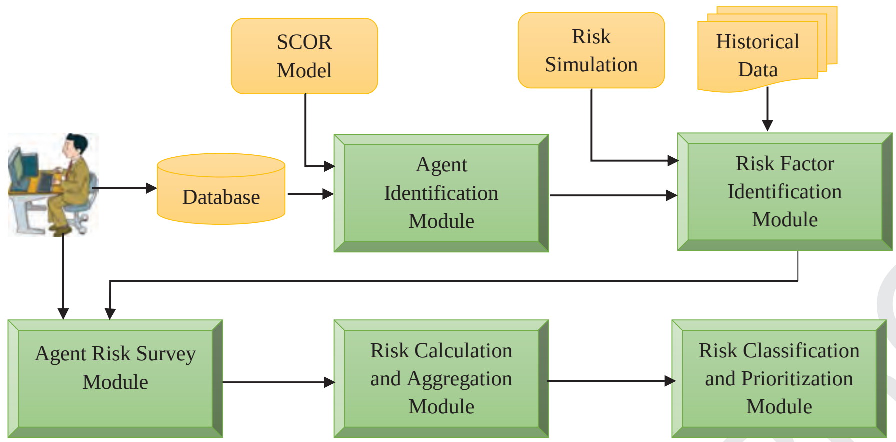

Fig. 9. An illustration of the Risk Assessment tool.

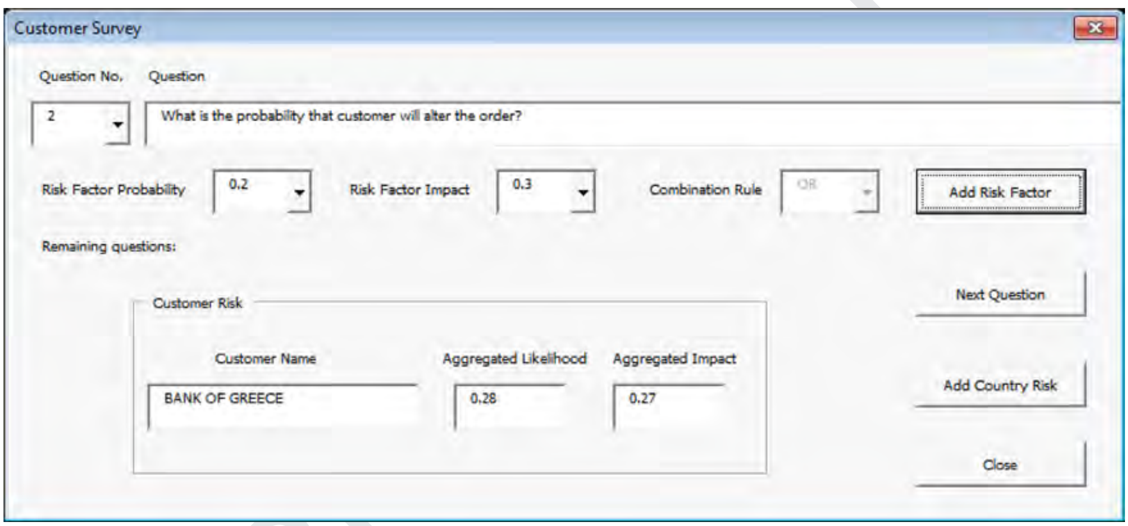

Fig. 10. Customer agent survey module.

calculation and aggregation, and risk classification and prioritization. The software tool was developed using VBA and SQL programming languages. The Agent Identification module identifies the main agents in the supply chain, mainly based on SCOR model. Main agents in the supply chain include: environment, suppliers, supplier hubs, manufacturers, distribution centers, and customers. Depending on the supply chain structure, risk can transfer from one agent to another and affect the whole supply chain. Risk Factor Identification module focuses on identifying the main risk factors that can impact the supply chain. A risk may be caused by one or more risk factors. Risk factors are identified based on historical data and/or simulation models as well as the subject matter experts. The Agent Survey module includes a set of questions for the agent to estimate the likelihood and impact of the risk factors and then the Risk Calculation and Aggregation module calculates the aggregated likelihood and impact of the agent risk (see Fig. 10). For each risk factor, the respondents are asked to estimate the probability of the risk with a number between 0 and 1 and the estimated impact (also with a value between 0 and 1). The Risk Classification and Prioritization module classifies the risks based on their final scores into high, medium, and low risks. The risks are then prioritized so that the high risks can be mitigated first. The main menu of the RRA software tool is shown in Fig. 11. There are seven agents in the integrated supply chain and agents can be added or deleted. Each agent has a drop down menu which include all the instances of that agent. The risk score for each agent is calculated based on the aggregated likelihood and impact obtained from the Risk Survey module. The calculation of the risk score is based on the fuzzy inference system as discussed earlier. Other options that are considered by the RRA tool include connection to database, connection to a simulation model to assess the risks and their impact, aggregating the risk per product type, and generating risk reports.

5. Risk assessment case study

In order to assess the validity of the proposed framework, the RRA software tool was tested in manufacturing environment for assessing the risk in its integrated supply chain. The company has three main product types; product A, product B and product C. Only the main parts and their associated suppliers were considered in the study. The risk calculations were performed to estimate the final risk scores for the three products. The company has a database for risk data and estimates of the risk likelihood and impact are obtained from surveys distributed to supply chain risk experts. It was found that the final risk scores for the three products, A, B, and C, are 25, 19, and 18%, respectively. This means that the risk levels for products B and C are low (green) where the risk level for product A is medium (yellow) and hence mitigation policies are needed to reduce the risk level. The risk calculations procedure for product A is presented in Fig. 12 and the risk report generated by the RRA software is shown in Fig. 13. The data collected for the risk likelihood for the five parts are: 0.09, 0.30, 0.21, 0.17, and 0.54. The risk impacts for the five parts are:

Fig. 11. Main menu of Rapid Risk Assessment (RRA) tool.

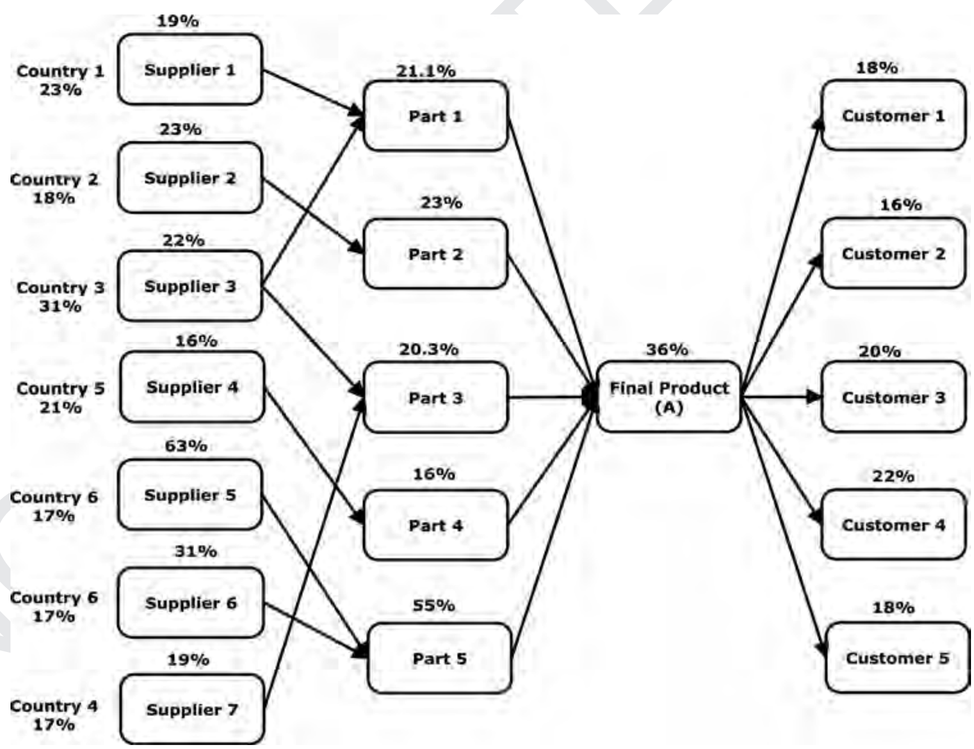

Fig. 12. Risk calculations for Product A.

0.74, 0.55, 0.52, 0.10, and 0.52, respectively. Using the fuzzy inference system, the calculated risks for the five parts are: 21.1, 23, 20.3, 16, and 55%, respectively. For customers, the risk likelihoods are: 0.31, 0.22, 0.50, 0.07, and 0.11, respectively. The risk impacts for customers are: 0.20, 0.09, 0.33, 0.74, and 0.39, respectively. Based on the values of likelihood and impact, the customers' risk values were calculated by the fuzzy inference system as: 18, 16, 20, 22, and 18%, respectively. For the manufacturing sites, the risk parameters are 0.33 and 0.45. Using the fuzzy inference system, the manufacturing site's risk is 21%.The risk parameters for product A, likelihood and impact, are then calculated based on the risk parameters of customers, parts, and manufacturing site as:

$$P_A^r = 1 - \prod_{l=1}^{L}(1-\varepsilon_{pl}P_l^c)\prod_{q=1}^{Q}(1-\varepsilon_{pq}P_q^o)\prod_{k=1}^{K}(1-\varepsilon_{pk}P_k^t)$$
$$= 1-(1-0.19)(1-0.22)(1-0.33) = 0.58$$

$$L_A^r = \frac{\sum_{l=1}^{L}\varepsilon_{pl}L_l^cP_l^c + \sum_{q=1}^{Q}\varepsilon_{pq}L_q^oP_q^o + \sum_{k=1}^{K}\varepsilon_{pk}L_k^tP_k^t}{\sum_{l=1}^{L}\varepsilon_{pl}P_l^c + \sum_{q=1}^{Q}\varepsilon_{pq}P_q^o + \sum_{k=1}^{K}\varepsilon_{pk}P_k^t}$$
$$= \frac{0.64+0.34+0.15}{1.31+0.91+0.33} = 0.44$$

Please cite this article as: F. Aqlan, A software application for rapid risk assessment in integrated supply chains, Expert Systems With Applications (2015), http://dx.doi.org/10.1016/j.eswa.2015.08.028

County	Country Risk	Supplier	Supplier Risk	Agg. Suplier Risk	Part	Part Risk	Agg. Part Risk
Country 1	0.23	Supplier 1	0.51	0.42	Part 1	0.16	0.211
Country 3	0.31	Supplier 3	0.32	0.31			
Country 2	0.18	Supplier 2	0.27	0.22	Part 2	0	0.23
Country 3	0.31	Supplier 3	0.32	0.32	Part 3	0.2	0.223
Country 4	0.17	Supplier 7	0.19	0.18			
Country 5	0.21	Suplier 4	0.16	0.18	Part 4	0.17	0.16
Country 6	0.17	Supplier 5	0.63	0.5	Part 5	0.32	0.55
Country 6	0.17	Supplier 6	0.31	0.27			

Manufacturer	Manufacturer Risk
Manufacturer 1	0.21

Product	Product Risk
Product A	0.36

Customer	Customer Risk
Customer 1	0.18
Customer 2	0.16
Customer 3	0.2
Customer 4	0.22
Customer 5	0.18

Fig. 13. Risk report for Product A.

Using the fuzzy inference system with a likelihood value of 0.58 and an impact value of 0.44, the calculated risk for product A is 36%. This value of risk is considered high and the company needs to develop effective mitigation strategies to reduce the risk levels.

6. Conclusions and future work

Risk management in integrated has become increasingly important in today's competitive and globally dispersed environments. The existing supply chain risk management models and software are not comprehensive and are require a long time to perform the risk assessment process. This paper presented a framework for risk assessment in integrated framework. The major contributions of this research are two-folds. First, it proposes a framework for rapid assessment of risks in integrated supply chains by combining qualitative and quantitative techniques taking into consideration risk correlations and uncertainties. The proposed framework helps decision makers assess the risks per product type and compare and prioritize the risks of the different product types. Second, it develops a software application that helps the risk management decisions to be fast and easy. The proposed software was developed using VBA and SQL programming languages. The software tool is flexible and it allows the user to add or delete agents, connect to database, and connect to simulation models. Furthermore, the risk survey's questions can also be changed and/or replaced. The application of the proposed framework in a real manufacturing environment has been carried out to assess the proposed system. Results from the case study showed that the assessment obtained by the proposed framework agrees with what the risk management experts think about the risk levels in the company.

The major limitation of this research is that subjective weights are assigned to the risks to calculate the aggregated values. These weights are decided by the subject matter experts. Usually, higher weights are assigned to the higher risk values and based on this an equation can be developed to link the weights to the risk values without having the decision makers assign them. Furthermore, this research did not discuss the two risk factor identification methods: simulation and historical data analysis. As an extension to the work performed in this research, the risk factor identification methods, namely simulation and historical data, can be further investigated. Data mining and big data analysis techniques can also be utilized for risk management considering structured and unstructured data. In addition, to deal with the uncertainty inherent with the risk data, methods other than fuzzy logic can be used such as Monte Carlo Simulation, Utility Theory, and Information Theory.

Uncited references

Alpan & Gonca, 2010, Aqlan & Lam, 2015b

References

Alpan, G., & Gonca, T. (2010). Risk assessment and management for supply chain networks: a case study. *Computers in Industry, 61*(3), 250–259.
Aqlan, F., & Ali, E. M. (2014). Integrating lean principles and fuzzy bow-tie analysis for risk assessment in chemical industry. *Journal of Loss Prevention in the Process Industries, 29*, 39–48.
Aqlan, F., & Lam, S. S. (2015a). A fuzzy-based integrated framework for supply chain risk assessment. *International Journal of Production Economics, 161*, 54–63.
Aqlan, F., & Lam, S. S. (2015b). Supply chain risk modeling and mitigation. *International Journal of Production Research, 53*(18), 5640–5656.
Blackhurst, J., & Wu, T. (Eds.). (2009). *Managing supply chain risk and vulnerability: Tools and methods for supply chain decision makers* (p. 12). London, UK: Springer .
Bogataj, D., & Bogataj, M. (2007). Measuring the supply chain risk and vulnerability in frequency space. *International Journal of Production Economics, 1–2*(108), 291–301.
Chen, J., Sohal, A., & Prajogo, D. (2013). Supply chain operational risk mitigation: a collaborative approach. *International Journal of Production Research, 75*(1), 2186–2199.
Chopra, S., & Sodhi, M. S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review, 46*(1), 52–61.
Diabat, A., Govindan, K., & Panicker, V. (2012). Supply chain risk management and its mitigation in a food industry. *International Journal of Production Research, 50*(11), 3039–3050.
Ebrahimnejad, S., Mousavi, S., & Seyrafianpour, H. (2010). Risk identification and assessment for build–operate–transfer projects: A fuzzy multi attribute decision making model. *Expert Systems with Applications, 37*(1), 575–586.
Fugini, M., Teimourikia, M., & Hadjichristofi, G. (2015). A web-based cooperative tool for risk management with adaptive security. *Future Generation Computer Systems* (in press).
Goh, M., Lim, J. Y., & Meng, F. (2007). A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research, 182*(1), 164–173.
Hamidi, H. (2011). A fuzzy MCDM model for allocating orders to suppliers in a supply chain under uncertainty over a multi-period time horizon. *Expert Systems with Applications, 38*(8), 9076–9083.
Hochrainer-Stigler, S., Mechler, R., & Mochizuki, J. (2015). A risk management tool for tackling county-wide contingent disasters: a case study on Madagascar. *Environmental Modelling and Software, 72*, 44–55.
Lim, S. J. (2010). *Risk response strategies in the supply chain: Examining attributes of stakeholders and risk atitude*. Master Thesis, Singapore Management University.
Merna, T., & Al-Thani, F. F. (2005). *Corporate risk management: An organizational perspective*. West Sussex, England: John Wiley & Sons.
Sarkar, A., & Mohapatra, P. K. (2009). Determining the optimal Size of supply base with the consideration of risks of supply disruptions. *International Journal of Production Economics, 122*(1), 122–135.
Schmitt, A. J. (2009). Quantifying supply chain disruption risk using Monte Carlo and discrete-event simulation. In *Proceedings of the Winter Simulation Conference* (pp. 1237–1248).
Sheffi, Y. (2002). Supply chain management under the threat of international terrorism. *International Journal of Logistics Management, 12*(2), 1–12.
Stornetta, A., Engeli, B., Zarn, J., Gremaud, G., & Sturla, S. (2015). Development of a risk management tool for prioritizing chemical harzard-food pairs and demonstration for selected mycotoxins. *Regulatory Toxicology and Pharmacology, 72*(2), 257–265.
Tse, Y., & Tan, K. (2011). Managing product quality risk in a multi-tier global supply chain. *International Journal of Production Research, 49*(1), 139–158.
Wakolbinger, T., & Cruz, J. M. (2011). Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts. *International Journal of Production Research, 49*(13), 4063–4084.
Waters, D. (2007). *Supply chain risk management: Vulnerability and resilience in logistics*. London, UK: Kogan Page Ltd.
Wu, T., Blackhurst, J., & Chidambaram, V. (2006). A model for inbound supply risk analysis. *Computers in Industry, 57*(4), 350–365.

Please cite this article as: F. Aqlan, A software application for rapid risk assessment in integrated supply chains, Expert Systems With Applications (2015), http://dx.doi.org/10.1016/j.eswa.2015.08.028