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# A proactive approach to supply chain risk management: Shifting orders among suppliers to mitigate the supply side risks

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## ABSTRACT

Globalization, e-trade, advanced technologies and emerging production techniques have increased supply chains' efficiency and added value. However, despite numerous advantages, these factors make supply chains more fragile and vulnerable to risks. For this reason, companies that perform supply chain risk management gain competitive advantage. In the past, supply chain managers mainly focused on reducing costs; but recently, they have begun to give importance to supply chain continuity and resiliency which have significant impacts on costs as well. Hence, conventional reactive planning has given way to proactive planning in supply chain risk management. In this study, the supply chain risk management process is investigated and a procedure is proposed in the risk mitigation phase. In the first stage of the proposed procedure, an initial procurement plan is obtained via a linear programming model, considering the cost criterion as the first priority. In the second stage, this plan is revised by including the risk criterion into the planning as the second priority. The aim of this procedure that enables proactive planning is to reduce the supply side risks. The model is tested with a hypothetical data set and the cost analysis is performed to evaluate the performance of the procedure. Finally, the whole supply chain risk management process including the proposed procedure is applied to an international automotive company.

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## 1. Introduction

We face many risks in our daily life and consent to live with them to some level in order to survive and conduct activities. For instance, driving a car embodies the risk of accident and potential consequences of life and material loss. People accept these consequences for the sake of the driving benefits and they prefer safer cars, fasten seat belts and obey traffic rules to mitigate the probability and/or the adverse impacts of risky events. They could not simply refrain from driving their cars to avoid risks because using other transportation methods also involves some other risks.

As in human life, it is impossible to survive and make money without taking risk in business life as well. Companies also must accept some degree of risk and apply risk mitigation strategies to gain a competitive advantage and make profit. For example, increasing globalization and e-trade yields lower raw material or product costs especially when procured from the Far East and provides economies of scale. However, long supply chains (SC) and intercontinental transportation are subject to numerous risks

arising from communication, geopolitical, cultural, transportation or legal complexities. If one or more of these risks emerge, firms are likely to encounter much higher costs rather than the financial advantage of supplying from intercontinental instead of local suppliers. Chopra et al. (2007) show that ignoring two kinds of risk sources as disruption and supply delays not only increases the use of more unreliable and cheap suppliers but also decreases the use of reliable suppliers. For example, Schmitt and Singh (2011) have expressed that one consumer packaged goods company's SC came to a halt due to a customs strike. When customs went on strike in a South American country, no raw materials could be shipped to their plant. While the plant had planned to carry three weeks' worth of raw material inventory, they happened to only have one weeks' worth on hand because additional material was in transit. Thus after a week, production shut down at that facility. This was a serious issue, as facility fixed costs and labor costs were still incurred. Only a few days' worth of production was not shipped on time, but the total cost to the company was estimated at a million dollars. This incident shows the importance of SC continuity and planning of facilities as back up for each other.

The art of risk management is not just in responding to anticipated events but in building a culture and organization that can respond to risk and withstand unanticipated events (Coleman, 2011). Most companies recognize the importance of risk assessment

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programs and use different methods, ranging from formal quantitative models to informal qualitative plans, to assess SC risks. However, most companies invested little time or resources for mitigating SC risks (Jianlin, 2011).

Although the number of academic studies on supply chain risk management (SCRM) has increased since the year 2000, use of quantitative models remained insufficient. Application of risk management by organizations has not been at the desired level. In a recent survey by Poirier and Quinn (2004), only one-third of the responding firms reported that they paid sufficient attention to SC vulnerability and risk mitigation actions. One finding is that the intellectual structure of the SCRM field made a statistically significant increase during 2000–2005 and evolved from passively reacting to vague general issues of disruptions towards more proactively managing SC risk from system perspectives (Tang and Musa, 2011). Ghadge and Dani (2012) have conducted a thorough study on the academic literature of the SCRM. They have noted that SCRM gathered more focus only after the 9/11 terrorist attacks in the USA and the radical increase is after 2004. According to this study which examines 120 papers published between 2000 and 2010; 54.16% are qualitative, 36.66% are quantitative and 9.16% are mixed regarding the research approach; 35.00% are risk identification, 14.33% are risk assessment, 5.83% are risk mitigation/control and 44.16% are holistic regarding risk management process; 56.33% are proactive, 23.33% are reactive and 20.83% are holistic regarding the risk mitigation approach.

Popular trends of our time such as lean manufacturing and JIT production, improving optimization techniques, shortening of product life, extending of transportation networks but shortening of lead times all expose SCs to more risks. Because of these reasons, firms should put more emphasis on the risk management process and create their procurement and production plans in the light of their risk assessment. A SC manager should consider every element of a SC while planning and executing SCRM. Since every member in a SC as a supplier, manufacturer, warehouse, retailer, customer etc. wants to achieve their own goals individually; the goal of one may increase the risk of another. A disruption in any part of a SC negatively affects every part of it. Hence, SC managers should see and evaluate the whole picture and navigate every member in one direction in terms of risk management. Risk criterion as well as cost criterion should be considered while making strategic decisions on significant issues regarding transportation routes, amount of production in each manufacturing facility, determination of risk attitude in case of a risk, and while choosing between two alternatives such as multiple versus single supplier, in-house versus global procurement.

A proactive planning procedure is proposed in this paper in light of these views. The main aim of this procedure is to take precaution against risky suppliers and to decrease the level of damage in case a disruption occurs. In a multi-supplier, multi or single manufacturer system, the initial procurement plan of a single commodity is obtained via the linear programming model with the objective of cost (purchasing and transportation cost) minimization. Then, risk assessments of all suppliers are conducted qualitatively and the risk profiles are obtained to be used in the second linear programming model that modifies the initial procurement plan. Since the identification of risk impact in terms of cost is very difficult prior to the occurrence of risk, including the risk criterion into a model in terms of cost is usually unrealistic. To prevent this handicap and reflect real world situations into a model more accurately, risk profiles are directly used to reflect the risk status of a supplier and to modify the initial procurement plan. The initial purchasing quantity of each supplier is proportioned to its risk profile and the product quantities to be maintained and to be transported to a less risky supplier are identified by this way. If the risk profile of a supplier is higher than the risk

criteria of the purchasing company as a result of the risk evaluation, that supplier can be eliminated directly from the supplier base. Both the first and the second models are capacity constrained. If the unit purchasing cost of a certain supplier is low but that supplier is more risky than the others, the purchasing quantity planned via the cost minimization merely is proportioned to its risk profile and some of the products may be purchased from the relatively less risky supplier considering the capacity of that supplier. The product transfusions from risky suppliers to relatively less risky (reliable) suppliers are modeled as a network. If a disruption occurs, the severity of any risk on the purchasing company will be low by means of this pre-disruption preparation procedure owing to the fact that the product quantity is reduced in advance according to the risk profile of that supplier. The proposed procedure is theoretical and can be used by manufacturers/assemblers of all sectors procuring single product from multi-suppliers.

The remainder of this paper is organized as follows. Second part is literature review. In the third part, we identify the framework for the risk management process consisting of five phases and propose a proactive approach as a risk mitigation strategy. In the fourth part, the proposed model is tested and verified with a hypothetical data set and cost analysis is performed to evaluate the performance of the procedure. In the fifth part, the proposed procedure and the model is applied to an automotive company. In the last part, we discuss the results and conclude with suggestions for future work.

## 2. Literature review

Effective mathematical tools for analyzing and understanding appropriate supply chain risk management are attracting much attention due to increasing interest on supply chain vulnerabilities. Although the studies on supply chain risk management are mostly qualitative and empirical, there are also qualitative and model-based researches in literature. For example; Arntzen et al. (1995) implemented a mixed integer programming model that is used for determining optimal supplier relationship, optimal supply network design, optimal supplier order allocation and optimal supply contract. Camm et al. (1997) propose an integer programming model for Proctor and Gamble that deals with supply network design and supplier selection. Levy (1995) presents a simulation model to examine the impact of demand uncertainty and supplier reliability on the performance of different supply networks and supply contracts. Lee and Tang (1998a, 1998b) propose a stochastic inventory model to examine the tradeoff between the consignment and turnkey arrangements under demand uncertainty (Tang, 2006). Kouvelis and Rosenblatt (2002) have studied the design of global facility networks and presented a mixed integer programming model. They investigate essential design tradeoffs of such networks and incorporate government subsidies trade tariffs and taxation issues. Smith and Huchzermeier (2003) have studied the global supply chain and risk optimization, and showed how real options add value to global manufacturing firms (Goh et al., 2007). Bogataj and Bogataj (2007) develop a parametric linear programming approach for measuring supply chain risks in terms of lead time perturbations. Mark et al. (2007) present a stochastic model of the multi-stage global supply chain network problem, incorporating a set of related risks as supply, demand, exchange and disruption. The firm's objective is to maximize its global after-tax profit subject to capacity constraints in each plant and demand requirements in each market. Hopp and Yin (2006) used a non-linear mixed integer programming (NLMIP) formulation to explain supply disruption caused by catastrophic failure. The aim of the study is minimizing total cost comprising of inventory and

protection costs. Effects of several different protection policies were analyzed for mitigating disruption risks. [Buffa and Jackson \(1983\)](#) used multi-objective mathematical programming to model a supplier selection problem. [Wadhwa and Ravindran \(2007\)](#) developed a three-criterion mathematical model to select suppliers with capacity constraints. [Xia and Wu \(2007\)](#) developed a four-objective mixed integer formulation for supplier selection under volume price discounts. [Bundschuh et al. \(2003\)](#) used an NLMIP model to investigate reliability and robustness in supply chains. [Sodhi \(2005\)](#) presents two risk measures for demand risk and inventory risk. He has proposed two linear programming models to manage demand and inventory risk in a consumer electronics supply chain.

There are also studies investigating strategies that enable supply chains to become more flexible so as to reduce the negative implications of the occurrence of certain events associated with supply, process and demand risks ([Tsay and Lovejoy, 1999](#); [Tomlin and Wang, 2005](#)). [Tomlin \(2006\)](#) analyses the efficiency of different strategies (multiple sourcing, excessive inventory, contingent re-routing) through an analytical model focusing on a single-product setting. [Zsidisin et al. \(2004\)](#) advocate proactive supply management tools, particularly those that focus on addressing supplier quality issues, improving supplier performance and preventing supply interruptions. [Berger et al. \(2004\)](#) use the decision analysis approach to determine the number of suppliers. They suggest the use of a Critical Ratio to make the single versus dual sourcing decision. [Treleven and Schweikhart \(1988\)](#) present a conceptual risk/benefit assessment model for sourcing decisions, suggesting that sourcing risks can be managed by either decreasing the probability of risk components or decreasing the impact for each of the risk components ([Manuj and Mentzer, 2008](#)). [Tang and Tomlin \(2008\)](#) present a stylized model for examining the impact of the number of suppliers on the supply cost. As a risk mitigation strategy, they propose that it is sufficient to order from a handful of suppliers to reduce supply cost risks. [Kull and Talluri \(2008\)](#) propose a combination of analytical hierarchy process and goal programming as a decision tool for supplier selection in the presence of risk measures and product life cycle considerations. [Tomlin \(2006\)](#) analyzed the supplier selection problem under supply disruptions via stochastic optimization. In his study, two suppliers are investigated; one reliable but more costly and the other less reliable but cheaper. He found that supplier's working performance and the nature of the disruptions are critical for supplier selection.

[Xiao and Yu \(2006\)](#) analyzed the effect of supply disruption on retailers. Profit maximization and revenue maximization are taken into account as strategy for retailers. [Babich \(2005\)](#) deals with the uncertainty problem via the theory of financial options. Supply chain disruption is considered as a Bernoulli random variable in the model. [Hendricks and Singhal \(2005\)](#) ran an empirical study using data from 885 firms and reported performance changes. In this study, inventory level and economic growth are used as performance indicators. They indicated that disruptions have negative effects on the performance of the firms. [Chen et al. \(2006\)](#) and [Haq and Kannan \(2006\)](#) applied fuzzy MCDM techniques for the selection of suppliers. [Mendoza et al. \(2008\)](#) proposed a three-phase multi-criteria method that uses AHP and goal programming to the supplier selection problem ([Ravindran et al., 2010](#)).

[Deng and Elmaghraby \(2005\)](#) proposed a tournament method for selecting the best set of suppliers. According to the tournament approach, a firm starts with a set of suppliers first, then tests and allows them to improve their specifications without any financial support.

There are also artificial intelligence applications associated with supplier selection. [Choy et al. \(2003\)](#) proposed an artificial neural network model to select and benchmark suppliers. The model is used to reduce the time of supplier selection in a company.

### 3. Methodology

The risk management process generally consists of three stages; risk identification, risk evaluation and risk mitigation ([Wagner and Bode, 2009](#); [Kleindorfer and Saad, 2005](#); [Tang, 2006](#)). In literature, some scientists separate the risk evaluation phase into two phases: risk measurement and risk assessment. All the assessments in risk management are based on the prediction of an unknown future. It should be monitored, revised and updated all the time because it is a dynamic process. Therefore, risk monitoring and control phase has also been included in the SCRM process recently.

In this study, risk analysis is performed in five stages, which are: risk identification, risk measurement, risk evaluation, risk mitigation and risk monitoring and control. The proposed risk mitigation procedure is explained in detail in [Section 3.4](#) and basic information about the other phases is given in the following sub-sections to acquaint the readers with the risk management process.

#### 3.1. Risk identification

Risk identification is the first and the most important stage of the risk management. For an efficient risk management, SC must be divided into elements such as suppliers, manufacturers, warehouses, distribution channels etc. and the risks associated with each element should be examined and identified specifically and elaborately. This is called SC mapping and risk registering.

Firms should form an SCRM department in their organization structure. The SC manager or logistics manager is responsible for SCRM in an organization. However, all employees in an organization are elements of SCRM. In all phases of SCRM, especially the risk identification and risk mitigation phases, the experience of every member of an organization should be taken into account. The more information sharing and flow there is in an SC, the greater the chance of having an effective SC. Total quality groups consisting of every kind of workers should be established to have an efficient risk register. [Christopher and Peck \(2004\)](#) and [Neiger et al. \(2009\)](#) propose the application of supply chain re-engineering techniques for the risk source and risk identification.

Registered risks in literature, historical records of the firm, opinions and experiences of workers and experts, internet sites created for this phase can all be used in this phase ([Jereb et al., 2012](#)). Identified risks can either be the same for all kinds of sectors or be specific to a sector such as automotive, electronics, chemistry etc. SC risks are categorized in various ways in literature. For example, [Jianlin \(2011\)](#) categorized SC risks as operational and disruption risks. Operational risks are referred to as the inherent uncertainties such as uncertain customer demand, uncertain supply and uncertain cost. Disruption risks are referred to as the major disruptions caused by natural and man-made disasters as earthquakes, floods, hurricanes, terrorist attacks, etc., or economic crises as currency evaluation or strikes. More detailed views of the SC risks are described as internal risks which either are inherent or arise more directly from management decisions, risks within the SC or risks in the external environment. Internal risks arise from operations within an organization. They might be inherent risks in operations as accidents, the reliability of equipment, loss of an information technology system, human errors and quality issues, or risks that arise more directly from managers' decisions as the choice of batch sizes, safety stock levels, financial problems and delivery schedules. There are SC risks which are external to the organizations but within the SC. These occur from the interactions between members of the SC and are principally risks from suppliers (reliability, availability of materials, lead times, delivery problems, industrial action, etc.) and risks from customers (variable demand, payments, problems with order

**Table 1**  
World economic forum's categorization of global risks.

Economic risks	Environmental risks	Geopolitical risks	Societal risks	Technological risks
Chronic fiscal imbalances	Vulnerability to geomagnetic storms	Critical fragile states	Backlash against globalization	Critical systems failure
Chronic labor market imbalances	Failure of climate change adaptation	Failure of diplomatic conflict resolution	Rising rates of chronic disease	Cyber attacks
Extreme volatility in energy and agriculture prices	Irremediable pollution	Entrenched organized crime	Rising religious fanaticism	Failure of intellectual property regime
Hard landing of an emerging economy	Land and waterway use mismanagement	Pervasive entrenched corruption	Vulnerability to pandemics	Massive incident of data fraud/theft
Major systemic financial failure	Unprecedented geophysical destruction	Terrorism	Water supply crises	Massive digital misinformation
Unmanageable inflation or deflation	Persistent extreme weather	Widespread illicit trade	Food shortage crises	Unintended consequences of climate change mitigation

processing, customized requirements, etc.). The main causes of these risks are inadequate cooperation between members and lack of visibility. External risks are external to the SC and arise from interactions with its environment, including accidents, extreme weather, legislation, pressure groups, crime, natural disasters, wars, etc. (Mason-Jones and Towill, 1998). World Economic Forum Insight Report's (2012) categorization of global risks and SC related risks in each category are presented in Table 1.

### 3.2. Risk measurement

There are two criteria used for the risk measurement; the probability and the impact of a risky event. Expected impact, which is the product of probability and impact, is referred to as the risk measurement.

A probability distribution function or occurrence frequency of a risky event is used to find the value of probability. In order to use probability functions, we must have historical data on that event first. The type of distribution function must be identified by fitting tests. Then, the parameters of the distribution function must be calculated and the probability of a risky event can be found. Although the probability values found by this method are more reliable and accurate, it is difficult to find the type of distribution function due to lack of required data. Data might be available for some risks such as currency rate and lead time but might be rare and insufficient for events as earthquake, terrorism etc. In this situation, the likelihood of an event can be used. Likelihood is related to the frequency of occurrence of an event. This method is more practical than and might be as accurate as the other method when experts evaluate the risky event meticulously.

The second component of the risk measurement is the impact of a risky event. It is very difficult to estimate and compute the impact in advance because a disruption in any part of the SC usually affects other parts as well. Risk impact is usually expressed in terms of cost but performance loss, physical loss, psychological loss, social loss, time loss etc. are also other types of impacts (Harland et al., 2003). Moreover, the impact of environmental events varies according to the firm's size. For instance, small companies might be affected more than large-scale companies from an economic crisis or currency rate risk.

The assessment model of risks must be simple because identification of the probability and the effect of the risk are based on subjective estimation. The model must therefore be understood as a method that provides direction. The primary aim of the model is not to provide an absolute value of risk, but rather to provide support in the decision-making process (Hallikas et al., 2002). The Military Standard, System Safety Program Requirements (MIL-STD 882C), which was released in 1993 by the USA Department of Defense, can be regarded as a cornerstone in risk analysis. This document proposes very practical and applicable methods in

determining the impact and likelihood of a risky event. Since MIL-STD 882C was prepared for the risk analysis of military units, impacts of risky events are identified in terms of death, injury, system failure or environmental loss. Tummala and Schoenherr (2011) have adapted the impact and likelihood categories of MIL-STD 882C to industry in their study. Impact categories are related to the performance of a firm that is exposed to a risky event.

As mentioned earlier, expected impact is the product of impact and probability of a risky event. The probability-impact matrix is a useful tool to visualize and define the expected impacts (Table 2) and is widely used in literature.

A risky event which is unlikely but has a high impact has an index of 8 out of 25. Both the likelihood and impact index of a risky event increases as we move towards the lower right of the matrix.

### 3.3. Risk evaluation

Risk evaluation is the process of comparing the results of risk analysis with risk criteria to determine whether the risk is acceptable or tolerable. Risk criteria are based on organizational objectives and can be derived from standards, laws, policies and other requirements (ISO Guide 73, 2009). It is impossible and unreasonable to refrain from all risks. At the end of the risk evaluation phase, a risk owner can select one of the four different strategies: avoid risk, reduce the probability and/or impact of risk, accept the occurrence of risk and prepare contingency plans (Baird and Thomas, 2008). Selection of the strategy mainly depends on the trade-off between the expected impact and the cost associated with the implementation of the selected strategy. Micheli et al. (2014) propose a quantitative decision support system (DDS) to select appropriate mitigation measures for supply chain risks. They do not propose a new mitigation measure but formulates a stochastic integer linear programming framework, which elaborates the supply chain managers' judgments' by way of utility functions and fuzzy-extended pairwise comparisons.

Risk profile is a measure that indicates the risk level of a supplier. It is calculated by summing the risk indices greater than the risk criteria of the firm.

$$R_t = \sum_{k=1}^K R_k * Z_k$$

$R_t$  = Total risk value

$$Z_k = \begin{cases} 0, & \text{risk index of } k^{\text{th}} \text{ identified risk is less than the risk criteria of the firm} \\ 1, & \text{risk index of } k^{\text{th}} \text{ identified risk is greater than or equal to the risk criteria of the firm} \end{cases}$$

$k$  = identified risks from 1 to  $K$

This categorization and the actions regarding risk indices can vary according to sector and the managers' risk attitude.

**Table 2**  
Probability–impact matrix

		Impact					
		Very low	Low	Medium	High	Very high	
		1	2	3	4	5	
Likelihood	Very unlikely	1	1	2	3	4	5
	Unlikely	2	2	4	6	8	10
	Medium	3	3	6	9	12	15
	Likely	4	4	8	12	16	20
	Very likely	5	5	10	15	20	25

**Table 3**  
Risk mitigation strategies in supply chains.

Avoidance	Dropping specific products/geographical markets/supplier and/or customer organizations
Control	Vertical integration
	Increased stockpiling and the use of buffer inventory
Co-operation	Maintaining excess capacity in productions, storage, handling and/or transport
	Imposing contractual obligations on suppliers
	Joint efforts to improve SC visibility and understanding
Flexibility	Joint efforts to share risk-related information
	Joint efforts to prepare SC continuity plans
	Postponement
	Multiple sourcing
	Localized sourcing

3.4. Risk mitigation and the proposed procedure

Risk mitigation makes use of the data collected in the previous stage to address potential risks with the right countermeasures. This includes classic mitigation strategies which are implemented before the risky event and contingency plans implemented after the risky event (Kern, 2012). Kleindorfer and Saad (2005) argue that prevention is better than a cure, requiring risk managers to act fast and treat urgent risks first.

Risk mitigation strategies can be classified into two groups: reactive and proactive. In a reactive approach, no action is taken before the occurrence of a risky event but it is implemented to mitigate the impact and/or probability after it occurs. In these kinds of strategies, there is no plan to reduce the risk probability. Although there are plans to reduce the impact, they are implemented after the occurrence of the risky event. In a proactive approach, plans are implemented to mitigate the risks before they occur. This approach may include the execution of plans either to decrease the probability or to reduce the impact of the risky event in advance.

Jüttner et al. (2003) summarize examples of some risk mitigation strategies as in Table 3.

In this study, a mitigation strategy is proposed to decrease the expected impact of risk. The flowchart of the procedure is presented in Fig. 1.

In this procedure, cost is considered to be the first priority goal. The problem can be modeled through a bipartite complete directed graph  $G(V_1 \cup V_2, A)$ , where the vertices in  $V_1$  stand for the suppliers, the vertices in  $V_2$  represent the manufacturing/assembly plants and the arcs in  $A = V_1 \times V_2$  are associated with the product flows between the suppliers and the manufacturing/assembly plants. In the first stage of this method, an initial procurement plan is created by the following linear programming model.

$$Mincost = \sum_{i \in V_1} P_i \sum_{j \in V_2} y_{ij} + \sum_{i \in V_1} \sum_{j \in V_2} T_{ij} * y_{ij} \tag{1}$$

$$\sum_{j \in V_2} y_{ij} \leq C_i \quad i \in V_1 \tag{2}$$

$$\sum_{i \in V_1} y_{ij} \geq D_j \quad j \in V_2 \tag{3}$$

$$y_{ij} \geq 0 \quad i \in V_1, \quad j \in V_2 \tag{4}$$

i; suppliers

j; manufacturers/assemblers

$P_i$ = unit purchasing price of supplier i

$y_{ij}$ = quantity to be transported from supplier i to manufacturer j



Fig. 1. Flowchart of the procedure.

$T_{ij}$ = unit transportation cost from supplier i to manufacturer j

$C_i$ = capacity of supplier i

$D_j$ =demand of manufacturer j

In the second stage, this plan is modified considering the risk profiles of suppliers. The order quantity from a supplier which is found by the minimum cost criterion is proportioned to the risk profile of that supplier and this amount is transferred to a more reliable supplier. To achieve this aim, the difference between suppliers in terms of risk is identified. For this, the total risk index ( $R_i$ ) (risk profile) of the least risky supplier is set to zero and the risk profile value of this supplier is subtracted from the risk profiles of other suppliers and then values are normalized. By this way, the risk differentiation between all suppliers is maintained (Table 4). (Let Supplier-2 be the least risky among n suppliers).

These normalized risk values represent the risk status of suppliers according to the least risky supplier. So, they can also be used to find the quantity to be transferred as a percentage of the initial procurement quantity (Table 5).

There is not an actual product movement in this transfer but it is a transfer in plans. In other words, the revised procurement plan is put in action and products are ordered only after the analysis is done. Suppliers with relatively less cost and lower risk profiles are highly utilized considering capacity constraint. Since the model includes capacity constraints, the quantity to be transferred from suppliers with high risk profiles to suppliers with low profiles are limited to the capacity of the latter. After the transfer quantity is calculated, how much of it will be transferred to which supplier is determined via a linear programming model. In this directed network, there is an arc from supplier i to a relatively less risky supplier j.

Decision variables ( $X_{ij}$ ) in the linear programming model are the product quantities transferred from supplier i to supplier j. The objective is to maximize the product flow from a risky supplier to a relatively less risky supplier. So the parameters of the decision variables in the objective function are the positive differences between the normalized risk values of suppliers. The objective function value does not represent any quantity but since the objective function is maximization, it satisfies the condition of transfer from a risky supplier to a less risky supplier. There is one constraint for the lowest and the highest risky nodes (suppliers) each and two constraints for all other nodes.

$$Maxz = \sum_{ij} N_{ij} * X_{ij} \tag{5}$$

**Table 4**  
Normalized risk values.

Suppliers	Total risk value	Relative total risk values based on the least risky supplier	Normalized values
Supplier-1	$R_{t1}$	$R_{t1} - R_{t2}$	$R_{N1} = (R_{t1} - R_{t2}) / R_{GT}$
Supplier-2	$R_{t2}$	0	$R_{N2} = 0$
Supplier-	$R_t$	$R_t - R_{t2}$	$R_{Nt} = (R_t - R_{t2}) / R_{GT}$
Supplier-n	$R_{tn}$	$R_{tn} - R_{t2}$	$R_{Nn} = (R_{tn} - R_{t2}) / R_{GT}$
Total		$R_{GT}$	1

**Table 5**  
Parameters used in the model.

Suppliers	Number of products procured according to min cost	Normalized risk values	Product to be transferred	Product to be kept in the supplier	Remaining capacity of the supplier
Supplier-1	$Q_{c1}$	$R_{N1}$	$Q_{c1} * R_{N1}$	$Q_{c1} - (Q_{c1} * R_{N1})$	$RC_1$
Supplier-2	$Q_{c2}$	$R_{N2}$	$Q_{c2} * R_{N2}$	$Q_{c2} - (Q_{c2} * R_{N2})$	$RC_2$
Supplier-	$Q_c$	$R_N$	$Q_c * R_N$	$Q_c - (Q_c * R_N)$	$RC$
Supplier-n	$Q_{cn}$	$R_{Nn}$	$Q_{cn} * R_{Nn}$	$Q_{cn} - (Q_{cn} * R_{Nn})$	$RC_n$

$$\sum_j X_{ij} \leq Q_{Ti} \forall i \neq j \tag{6}$$

$$\sum_k X_{ki} - \sum_j X_{ij} \leq C_{Ri} \tag{7}$$

where  $N_{ij}$  is the positive difference between the normalized risk value of the node (supplier) i and node j.

- J indicates all suppliers less risky than supplier i,
- $Q_{Ti}$  is the quantity to be transferred from supplier i,
- K indicates all suppliers more risky than supplier i,
- $C_{Ri}$  is the remained capacity of supplier i.

Constraint (7) satisfies the condition that the difference between the quantity entering and leaving the node cannot be greater than the remained capacity of that supplier.

Multi-supplier vs. single supplier strategy is still an ongoing debate. A multi-supplier is a kind of alternative course of action towards disruptions and provides cost advantage due to competitiveness but it causes extra burden in management activities and increases paperwork costs. Besides, it may not be possible to find a number of suppliers in some sectors or regions. A single supplier strategy enables a close relationship with suppliers and control but may be more risky and costly. For these reasons, optimum strategy should be to limit the supplier base and increase the coordination, cooperation and information flow (Cruz and Liu, 2011). Regarding these ideas and in accordance with real world situations, we use multiple but limited suppliers in our model.

### 3.5. Risk monitoring and control

The risk management process is a cycle and the risk monitoring and control phase enables this process to be dynamic. Since risk is related to the future, events should be observed and the data about events should be updated and assessed all the time. This phase includes both observations about previous assessments and observations about changing situations and environment. New risks may be identified and/or new judgments about previously identified risks may be revised by means of this phase. Information systems should be utilized and a high coordination and information sharing system should be established for efficient monitoring and control. Real time observation and tracking is also very critical for efficient risk monitoring.

## 4. Numerical example and verification of the model

### 4.1. Numerical example

A single-echelon with suppliers and manufacturers that are in the same and/or different geographical region, single commodity, single period, capacitated model is proposed in this study (Fig. 2).

The capacity and unit purchasing price of each supplier is in Table 6, the demand of each manufacturer is in Table 7, the risk profile of each supplier is in Table 8 and the transportation costs from suppliers to manufacturers/assemblers are in Table 9.

The model to find the minimum procurement cost satisfying the demand of manufacturers is;

$$\begin{aligned} \text{Min cost} &= 38*y_{11} + 42.5*y_{12} + 42.5*y_{13} + 32.5*y_{21} + 37*y_{22} + 38*y_{23} \\ &+ 28.5*y_{31} + 31.5*y_{32} + 28.5*y_{33} + 30.5*y_{41} + 31.5*y_{42} \\ &+ 26*y_{43} + 32.5*y_{51} + 32.5*y_{52} + 33.5*y_{53} \end{aligned} \quad (8)$$

$$y_{11} + y_{12} + y_{13} \leq 47000 \quad (9)$$

$$y_{21} + y_{22} + y_{23} \leq 92000 \quad (10)$$

$$y_{31} + y_{32} + y_{33} \leq 49000 \quad (11)$$

$$y_{41} + y_{42} + y_{43} \leq 95000 \quad (12)$$

$$y_{51} + y_{52} + y_{53} \leq 44000 \quad (13)$$

$$y_{11} + y_{21} + y_{31} + y_{41} + y_{51} \geq 95000 \quad (14)$$

$$y_{12} + y_{22} + y_{32} + y_{42} + y_{52} \geq 74000 \quad (15)$$

$$y_{13} + y_{23} + y_{33} + y_{43} + y_{53} \geq 80000 \quad (16)$$

$$y_{ij} \geq 0 \quad (17)$$

Model is solved with Microsoft Excel and the optimal solution is presented in Table 10.

Total cost=7,860,000 unit.

This procurement plan is obtained without the consideration of risk criterion. The procurement quantity for each supplier found by the cost criterion should be modified in proportion to its risk profile.

According to Table 8, Supplier-2 is the most reliable and Supplier-3 is the most risky supplier. Product transfer will be performed from a risky supplier to a relatively less risky supplier by using the values in Table 8. In order to achieve this, the value of 32,

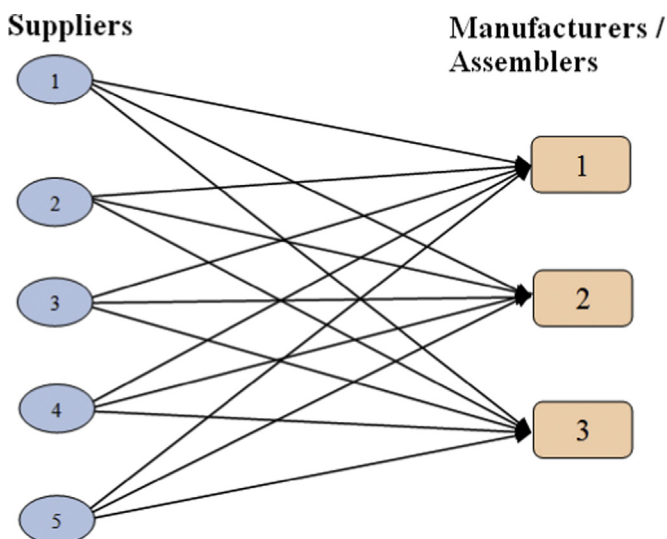


Fig. 2. Supply chain network.

Table 6  
Capacity and unit purchasing price of each supplier.

Supplier	1	2	3	4	5	Total
Capacity (C <sub>i</sub> )	47,000	92,000	49,000	95,000	44,000	327,000
Unit price (P <sub>i</sub> )	29.5	24	21.5	20.5	24.5	

Table 7  
Demand of each manufacturer/assembler.

Manufacturers/assemblers	1	2	3	Total
Demand (D <sub>i</sub> )	95,000	74,000	80,000	249,000

Table 8  
Risk profile of each supplier.

	Supplier-1	Supplier-2	Supplier-3	Supplier-4	Supplier-5
Risk profiles (R <sub>ri</sub> )	50	32	66	56	60

Table 9  
Transportation costs from suppliers to manufacturers/assemblers (T<sub>ij</sub>).

	Manufacturers/assemblers (j)		
	1	2	3
Suppliers (i)	1	8.5	13
2	8.5	13	14
3	7	10	7
4	10	11	5.5
5	8	8	9

Table 10  
Optimal solution.

	Manufacturers/assemblers (j)			Total
	1	2	3	
Suppliers (i)	1	0	0	0
2	61,000	0	0	61,000
3	34,000	15,000	0	49,000
4	0	15,000	80,000	95,000
5	0	44,000	0	44,000
Total	95,000	74,000	80,000	249,000

the most reliable, is subtracted from other supplier's risk profile values. Since there will be no product transfer from Supplier-2 to the others, zero is the base value and the differences between the risk profiles of suppliers remain the same. Finally, these values are normalized (Table 11).

The product transfer network based on the risk profiles of suppliers is presented in Fig. 3 and the parameters used in the model are presented in Tables 12 and 13.

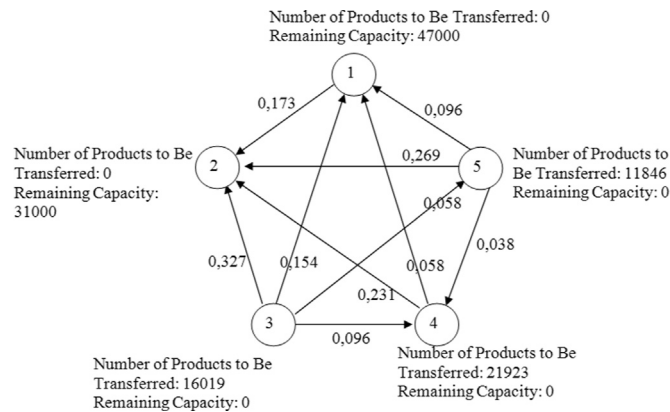
The model to transfer the products from a risky supplier to a relatively less risky supplier is:

$$\begin{aligned} \text{Max } z &= 0.173*X_{12} + 0.231*X_{42} + 0.269*X_{52} \\ &+ 0.327*X_{32} + 0.058*X_{41} + 0.096*X_{51} \\ &+ 0.154*X_{31} + \\ &+ 0.038*X_{54} + 0.096*X_{34} + 0.058*X_{35} \end{aligned} \quad (18)$$

$$X_{31} + X_{41} + X_{51} - X_{12} \leq 47000 \quad (19)$$

**Table 11**  
Normalized risk values.

Suppliers	Total risk value (risk profile)	Relative risk value based on the least risky supplier	Normalized values
Supplier-1	50	18	0.173
Supplier-2	32	0	0
Supplier-3	66	34	0.327
Supplier-4	56	24	0.231
Supplier-5	60	28	0.269
Total		104	1



**Fig. 3.** Product transfer network based on the risk profiles of suppliers.

$$X_{12} \leq 0 \tag{20}$$

$$X_{12} + X_{32} + X_{42} + X_{52} \leq 31000 \tag{21}$$

$$X_{31} + X_{32} + X_{34} + X_{35} \leq 16019 \tag{22}$$

$$X_{34} + X_{54} - X_{41} - X_{42} \leq 0 \tag{23}$$

$$X_{41} + X_{42} \leq 21923 \tag{24}$$

$$X_{51} + X_{52} + X_{54} \leq 11846 \tag{25}$$

$$X_{35} - X_{51} - X_{52} - X_{54} \leq 0 \tag{26}$$

$$X_{ij} \geq 0 \tag{27}$$

where  $X_{ij}$  is the number of products to be transferred from supplier  $i$  to supplier  $j$ .

Eqs. (19), (21), (23) and (26) are the capacity constraints, (20), (22), (24), and (25) are for the products to be transferred. The model is solved via Microsoft Excel in seconds and the optimal solution is presented in Table 14.

The modified procurement plan is presented in Table 15.

**Table 12**  
Parameters used in the model.

Suppliers	Min cost procurement plan	Normalized risk values	Number of products to be transferred	Number of products to be kept in the supplier	Remaining capacity of the supplier
Supplier-1	0	0.173	0	0	47,000
Supplier-2	61,000	0	0	61,000	31,000
Supplier-3	49,000	0.327	16,019	32,981	0
Supplier-4	95,000	0.231	21,923	73,077	0
Supplier-5	44,000	0.269	11,846	32,154	0

**Table 13**  
Difference between the normalized risk values of suppliers ( $R_{ij}$ ).

$R_{12}$	$R_{42}$	$R_{52}$	$R_{32}$	$R_{41}$	$R_{51}$	$R_{31}$	$R_{54}$	$R_{34}$	$R_{35}$
0.173	0.231	0.269	0.327	0.058	0.096	0.154	0.038	0.096	0.058

**Table 14**  
Optimal solution.

$X_{12}$	$X_{42}$	$X_{52}$	$X_{32}$	$X_{41}$	$X_{51}$	$X_{31}$	$X_{54}$	$X_{34}$	$X_{35}$
0	3135	16,019	11,846	18,788	0	0	0	0	0

4.2. Verification of the model

The proposed model is tested 10 times with randomly generated data and verified. Although five suppliers are more than enough for a single commodity in a real world situation, the model is also tested 10 times for 10 suppliers (nodes) and the solution is obtained in seconds without malfunction.

The benefits of the SCRM process cannot be realized before the occurrence of a risky event. For this reason, the costs incurred by the risk management process may be seen as unnecessary and this may prevent the application of SCRM. However, costs that the companies will face in case a disruption occurs are very likely much more than the costs incurred by the SCRM activities. It is certain that there should be a trade-off between these two costs. For this reason, cost analysis is performed for the 10 data set and statistical results are presented in Table 16.

As it is seen in Table 16, the inclusion of risk criterion into the procurement plan yields average of 2.60% increase in costs. Based upon the sample data, a 95% confidence interval for the population mean of cost increase is between 1.32% and 3.88%. Based on an analysis of 827 disruption announcements made over a 10 year period, Hendricks and Singhal (2005a) found that companies suffering from the occurrence of uncertain events experienced 33–40% lower stock returns relative to their industry benchmarks. When compared to this reality, the cost increase incurred by the proposed procedure is considerably low. By means of this proactive approach which reduces the risk, companies can decrease the vulnerability of their SCs and gain competitive advantage.

5. Automotive industry application

In the automotive industry, protecting the assembly line from delays due to missing or non-conforming parts is a paramount concern because automotive SCs are set to the pace of assembly lines. Automotive assembly lines may stop if even a minor supplier has a production interruption. Any disruption along the chain threatens the whole operation. A production breakdown in the automotive industry can cause economic losses of more than \$100 million per day. So they take great care to protect themselves from the risks involved (James, 2001). An ordinary car is composed of



**Table 15**  
Initial and revised procurement plans.

Suppliers	Min cost procurement plan	Risk profile	Procurement plan considering cost and risk criteria
1	0	50	18,788
2	61,000	32	92,000
3	49,000	66	32,981
4	95,000	56	73,077
5	44,000	60	32,154
Total	249,000	–	249,000

**Table 16**  
Statistical results of the cost analysis.

Test #	Increase in procurement cost	Increase in transportation cost	Increase in total cost
1	3.626%	8.559%	4.741%
2	3.235%	16.859%	5.801%
3	0.983%	– 1.080%	0.473%
4	1.999%	– 0.426%	1.383%
5	2.260%	6.179%	3.250%
6	2.706%	0.206%	2.156%
7	1.659%	0.615%	1.395%
8	3.542%	6.109%	4.188%
9	0.229%	5.176%	1.338%
10	0.806%	3.160%	1.286%
Mean	2.10%	4.54%	<b>2.60%</b>
Standard Deviation	1.19%	5.43%	1.79%
Variance	0.01%	0.30%	0.03%
Confidence interval (%95)	$1.25\% \leq \mu \leq 2.95\%$	$0.65\% \leq \mu \leq 8.42\%$	<b><math>\leq \mu \leq 3.88\%</math></b>

nearly 5000 parts and hence, OEMs work with lots of suppliers. For these reasons, automobile sector is chosen for application.

Logistics and procurement managers of an international automotive company in Turkey are interviewed for the procedure. In the risk identification phase, list of common risks is created via literature review first. Then this list is examined with the managers and consensus is achieved. The impact (Table 17) and likelihood (Table 18) of risky events are determined by taking aforementioned characteristics of the automotive SC and case studies in literature (Waters, 2011; Thun and Hoenig, 2011; Wagner et al., 2009; Singh et al., 2005; Iyer et al., 2009; Blome et al., 2012; Wagner and Camargos, 2012) into account and by interviewing the expert group.

As it is seen in Table 17 and Table 18, time intervals for automotive sector are so narrow in our current economic environment.

The probability-impact matrix (Table 19) is formed by using Table 17 and Table 18.

In this study, risk evaluation categories and risk criteria are obtained from the managers of the firm (Table 20).

In this table, a risk index of 2 is identified as a lower bound because no risk mitigation strategy is necessary for such kind of risks. A risk index of 16 is identified as an upper bound because a supplier with this level of risk is should be eliminated. It is most

**Table 17**  
Risk impact categories for automotive supply chain.

Risk impact	Definition	Impact index
Catastrophic	Cease of production for 1 week and more	5
Serious	Cease of production for 2–3 days	4
Moderate	Slowdown of production for 3–5 days	3
Minor	Decrease in customer service level	2
Negligible	Unaffected customer service level due to inventory on hand	1

**Table 18**  
Likelihood categorization for automotive supply chain.

Risk Likelihood	Definition	Likelihood Index
Usually	At least once a week	5
Often	1–2 times a month	4
Sometimes	1–2 times in 6 months	3
Seldom	Once a year	2
Rare	Once every 2 years and up	1

likely unreasonable to try to mitigate such a high level risk index. Risk criteria of the firm is determined as 6. So indexes between 6 (inc.) and 15 (inc.) are undesirable and measures should be taken to them.

The product under consideration is a safety camera system inside a bus. It is procured from three different firms in Germany. Demand for the camera system is 650 pieces a year. 70% of cameras (455 pcs.) are procured from firm A, 20% (130 pcs.) is procured from firm B and 10% (65 pcs.) is procured from firm C. The yearly capacities of firms are 600 pcs., 250 pcs. and 100 pcs. respectively.

The results of risk identification, measurement, evaluation and risk profiles of suppliers are in Table 21.

Since three firms are in the same country, some risk values (e.g. currency rate risk) are same for all. For this reason, these kinds of risks are eliminated in the evaluation phase.

As it is seen in Table 21, Supplier-B is the most risky and C is the most reliable supplier.

Normalized risk values of Suppliers are in Table 22.

The number of cameras to be transferred from a supplier to a relatively less risky supplier is calculated via normalized values and presented in Table 23.

The product transfer network is presented in Fig. 4.

Linear programming model for the product transfer is;

$$\text{Max } z=0.625 * X_{BC} + 0.375 * X_{AC} + 0.25 * X_{BA} \quad (28)$$

$$X_{BC} + X_{AC} \leq 35 \quad (29)$$

$$X_{BA} - X_{AC} \leq 145 \quad (30)$$

$$X_{BA} + X_{BC} \leq 81 \quad (31)$$

$$X_{AC} \leq 170 \quad (32)$$

Optimal solution of the model is;

$$X_{AC} = 0$$

$$X_{BC} = 35$$

$$X_{BA} = 46$$

The procurement plan modified according to the risk criterion is in Table 24.

As it is seen in the results, the number of cameras procured from Supplier-B is reduced 81 pcs. 35 pcs. of this amount will be procured from the most reliable Supplier-C and since its capacity is 100, the remaining 46 cameras will be procured from Supplier-A.

## 6. Conclusion and suggestions

Lower costs, commercial treaties, new markets, developing communication and internet opportunities are some of the advantages of globalization. However, cultural diversities, standardization difficulties, political instabilities and extended distances make SCs more vulnerable to risks. Today, SCRM ensures not only cost advantage but also competitive advantage. As presented in

**Table 19**  
Probability - impact matrix.

<b>Risk impact index</b>	<b>Unaffected customer service level due to inventory on hand (1)</b>	<b>Decrease in customer service level (2)</b>	<b>Slowdown of production for 3-5 days (3)</b>	<b>Cease of production for 2-3 days (4)</b>	<b>Cease of production for 1 week and more (5)</b>
Once every 2 years and up (1)	1	2	3	4	5
Once a year (2)	2	4	6	8	10
1-2 times in 6 months (3)	3	6	9	12	15
1-2 times a month (4)	4	8	12	16	20
At least once a week (5)	5	10	15	20	25

**Table 20**  
Risk evaluation categories.

<b>Risk index</b>	<b>Definition</b>
1 - 2	Acceptable, no action required
3 - 4 - 5	Acceptable, should be monitored
6 - 8 - 9 - 10 - 12 - 15	Undesirable and measures should be taken
16 - 20 - 25	Unacceptable

**Table 21**  
Risk Profiles of suppliers.

<b>Risk identification</b>	<b>Supplier-A Risk index</b>	<b>Supplier-B Risk index</b>	<b>Supplier-C Risk index</b>
Quality problems	6	12	3
Inability to adapt changes in customer demand	9	6	6
Increasing raw material prices	2	2	4
Bankruptcy of supplier	4	4	4
Supplier capacity risk	3	6	9
Machine breakdowns	9	6	3
Delivery chain disruptions	6	6	6
Malfunction of IT system	1	3	1
Accident (e.g. fire) risk	1	1	1
Industrial action risk (strike, lockout etc.)	2	2	2
Transportation failure	6	6	6
Import restrictions	4	4	4
Terrorist attack	2	2	2
Extreme weather conditions	2	2	2
Increasing customs duty	6	6	6
<b>Risk profile</b>	<b>42</b>	<b>48</b>	<b>33</b>

**Table 22**  
Normalized risk values of suppliers.

	<b>Risk profile</b>	<b>Normalized risk profile values</b>
A	42	0.375
B	48	0.625
C	33	0

**Table 23**  
Number of cameras to be transferred and retained.

	<b>Number of cameras to be transferred</b>	<b>Number of cameras retained in the supplier</b>
A	$455 \cdot 0.375 = 170$	285
B	$130 \cdot 0.625 = 81$	49
C	0	65

the literature review, the number of quantitative and model-based studies is more limited when compared to the number of qualitative and empirical ones. Within this context, a proactive planning procedure is proposed in this paper. The aim of this procedure is to take necessary precautions against the risky suppliers and decrease the level of damage in case a disruption occurs. The first stage of the proposed procedure is obtaining the initial procurement plan via linear programming with the objective of cost minimization, and the second stage is revising the initial procurement plan by integrating the risk criteria into the planning process. Risk assessment is conducted so as to identify risk profiles of all suppliers in the first step of this second stage. In the second step, the product quantities in the initial procurement plan are proportioned to risk profiles of the suppliers, and then the quantities to be kept in a supplier and those to be transferred to less risky suppliers are identified. In the third step, a product transfer linear programming model is established and in the last step, the

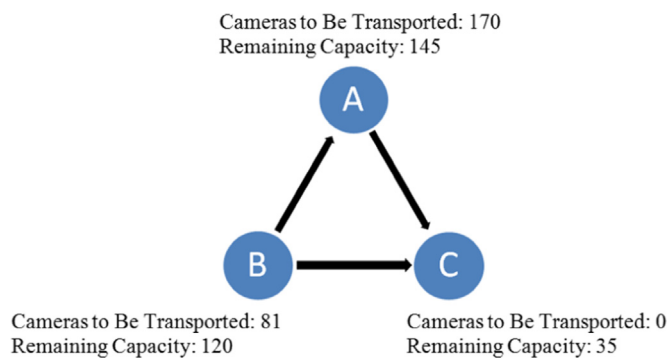


Fig. 4. Network for product transfusion.

Table 24

Modified procurement plan.

Supplier	Current procurement plan	Modified procurement plan
A	455	501
B	130	49
C	65	100
Total	650	650

new procurement plan is created by solving this linear programming model. This procedure is unique in that risk is quantified and included in the model not in terms of cost but as a profile value and it proposes a transfer of product strategy. This transfer plan is made before the order and suppliers receive the final product order prepared according to the cost and risk criteria. In the numerical example, the model is tested 10 times with a randomly generated hypothetical data set and verified. The cost increase incurred by the inclusion of risk criterion into the model is analyzed and a 95% confidence interval for the population mean of cost increase is observed to be between 1.32% and 3.88%. This cost increase is likely to be less than the cost that will be encountered in the case that a disruption occurs.

In the industry application phase, the whole supply chain risk management process including the proposed risk mitigation procedure is applied to an international automotive company in Turkey. Interior cameras are currently being supplied from 3 different suppliers in Germany according to the cost criterion only. The impact and likelihood of risky events for each supplier are identified by taking the characteristics of automotive SC and case studies in literature into account and by interviewing the expert group. The current procurement plan is modified via the proposed procedure and risk criterion is included in the procurement planning. Results are shared with the managers for future plans. Observing the results of risk mitigation strategies may take a long time due to the rare occurrence of some risks. Therefore, the observation of results and output of this procedure is still ongoing.

The procedure can be extended to multi-period, multi-commodity and multi-echelon SCs in further studies. Additionally, periodic and time-based risks, product risks and risks of other members of a SC can be investigated as well. Finally, the proposed procedure can be applied to different industries in order to evaluate its overall performance.

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