Chapter 4
Prioritization of Risks in Supply Chains

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Abstract Modern supply chains are very complex, with physical, financial, and information flows occurring simultaneously in order to ensure that products are delivered in the right quantities, to the right place in a cost-effective manner. Maintaining uninterrupted supply chain flows is a prerequisite for the success of a supply chain in the marketplace. But there are always associated risks in each of these flows which require suitable strategies to mitigate them. The issue of risks in supply chains has assumed importance in wake of the understanding that supply chain failures are fatal to the existence of all the partners’ in a supply chain. The severity of supply chain failures are more felt by small and medium enterprises (SMEs) who form the majority at tier II and tier III levels of a supply chain. This is because of the limited resources and lack of adequate planning to counter supply chain risks. Management of risk in supply chains is a multi-criteria decision making problem. The research presented in this chapter proposes a Fuzzy-AHP based framework to prioritize various risks in supply chains. An exhaustive literature review complemented with the experts’ opinion was undertaken from the perspective of SMEs to formulate a hierarchical structure of risks in supply chains. A fuzzy analytic hierarchical process (F-AHP) is then utilized to ascertain the relative weightings which are subsequently used to prioritize these risks. Understanding the priorities would help the firms to accord importance and develop suitable strategies to manage supply chain risks according to their relative importance. This provides effective management of scarce resources available to SMEs to manage risks resident in their supply chains.

4.1 Introduction

In today’s interconnected and information based economies, there have been dramatic shifts in the way companies interact, driven by both new technologies and new business models. This has led to firms’ exposure to new forms of risks, many
related to their extended supply chains. Though firms’ recognize that the survival in the modern business environment is no longer an issue of one firm competing against another firm but has, instead, become an issue of one supply chain competing against another supply chain the understanding that failure of any one link in the supply chain would have ripple effect on the overall supply chain has come rather late. But there is a growing realization among the companies that adopting supply chain risk management practices can yield continuous improvement of supply chain operations (Elkins et al., 2005).

The risk in a supply chain is the potential variation of outcomes that influence the decrease of value added at any activity cell in a chain, where the outcome is described by the volume and quality of goods in any location and time in a supply chain flow (Bogataj and Bogataj, 2007). The consequences of failing to manage risk have also become more severe. In addition to the direct impact on revenue and profit, disruptions in supply or demand can hurt a firm’s trading partners (e.g. customers and suppliers), since the interconnectedness of a supply chain has a ripple effect that affects the entire supply chain ecosystem (Shi, 2004). It is also reported that companies experiencing such disruptions under-perform their peers significantly in stock performance as well as in operating performance as reflected in costs, sales, and profits (Hendricks and Singhal, 2003, 2005). Thus, management of risk is, or should be, a core issue in the planning and management of any organization (Finch, 2004).

All the parts of supply chain could be impacted by a great variety of risks and the supply chain risks can have significant impact on the firm’s short-term and long-term performance. For the success of supply chain, the method to find ways of mitigating supply chain risks is critical to manage supply chain in unstable environment. In industries moving towards seamless supply chains the issue of supply chain risk handling and risk sharing along the supply chain is a topic of growing importance (Agrell, 2004; Gunasekaran et al., 2004). A key feature of supply chain risk is that, by definition, it extends beyond the boundaries of the single firm and, moreover, the boundary spanning flows can become a source of supply chain risks (Jüttner, 2005). Thus, to assess supply chain risk exposures, companies must identify not only direct risks to their operations, but also the potential causes or sources of those risks at every significant link along the supply chain (Christopher et al., 2002; Souter, 2000). The reasons that make an integrated approach to supply chain risks analysis and management important are (Harland, 2003; Shi, 2004; Faisal et al., 2006):

- Examining risk factors in isolation makes it difficult to understand their interactions.
- There may be an increase in risk management costs, since firms may unnecessarily hedge certain risks that are in reality offset by others.
- A fragmented approach to risk management also increases the likelihood of ignoring important risks.
- ICT revolution has eliminated the geographical boundaries for developing supply chain partnerships.
Even for known risks, it is important to consider their overall impact to the entire organization. Otherwise mitigation attempts may only introduce new risks, or shift the risk to less visible parts of the organization.

Failure to consider risk interactions can also cause firms to grossly underestimate their risk exposures.

There has been a recent surge in interest and publications from academics and practitioners regarding supply chain disruptions and related issues as supply chain risks can potentially be harmful and costly for the whole supply chain (Craighead et al., 2007). One important constituent of risk management process is the prioritization of risks. Prioritization helps a company to focus the decision making and risk management effort on the most important risks (Hallikas et al., 2002). Prioritization requires comparisons concerning the relative importance of each of the risk variables.

The purpose of this chapter is to contribute and provide a more complete understanding of risk in supply chains. It seeks to develop a model to assess relative importance of numerous risks inherent in the supply chain. The primary aim is to illustrate how organizations can prioritize risks in their supply chains. The main research problems addressed by the study presented in this chapter are:

1. What kinds of risks are associated with various supply chain flows?
2. How these risks can be prioritized?

After introduction, the remainder of this chapter is organized as follows. Sect. 4.2 presents literature review on risk, supply chain risk management, and risk mitigation strategies for supply chains. Risk taxonomy for supply chain is presented in Sect. 4.3. Next, Sect. 4.4 of the chapter discusses the methodology for prioritizing supply chain risks. A graphical representation of the model is shown in Fig. 4.1. In this part the numerical application of the proposed model for small and medium enterprises (SMEs) cluster is also discussed. Finally, Sect. 4.5 presents the concluding remarks of the chapter.

4.2 Literature Review

4.2.1 Risk

On a very general level, risk is defined as the probability of variance in an expected outcome and it differs from uncertainty in that risk has associated with it a probability of a loss and uncertainty is an exogenous disturbance (Spekman and Davis, 2004). According to Norrman and Jansson (2004) “risk is the chance, in quantitative terms, of a defined hazard occurring. It therefore combines a probabilistic measure of the occurrence of the primary event(s) with a measure of the consequences of that/those event(s)”. So to manage risk both an assessment of the probability of risk and its impact is necessary (Hallikas et al., 2002; Zsidisin et al., 2004; Hallikas et al., 2004).
As companies increasingly move towards inter-firm co-operation to achieve sustained competitive advantage, research in risk management began to examine risk management at the level of inter-organizational relationships and more recently at the level of supply chains and networks (Harland et al., 2003). Risk is perceived to exist when there is a relatively high likelihood that a detrimental event can occur and that event has a significant associated impact or cost (Zsidisin et al., 2004). A key feature of supply chain risk is that, the complexity makes it difficult for the exposed company to estimate the total financial losses, which contributes to the impediment in how to design risk mitigation solutions for supply chains. Current business trends that increase the vulnerability to risks in supply chains are (Harland et al., 2003; Normann and Jansson, 2004; Christopher and Lee, 2004; Cucchiella and Gastaldi, 2006):

- increased use of outsourcing of manufacturing and R&D to suppliers;
- globalization of supply chains;
- reduction of supplier base;
- more intertwined and integrated processes between companies;
- reduced buffers;
- shorter lead times requirements;
- shorter product life cycles and compressed time-to-market;
- increased product/service complexity; and
- capacity limitation of key components.

4.2.2 Supply Chain Risk Management

The degree of the vulnerability of a supply chain is determined to a large extent by the degree of complexity of the network (Nieger et al., 2008). In recent times the complexity has increased many-fold due to firms’ focus on their core competence and increased dependence on outsourcing. Top executives at Global 1000 firms now consider supply chain disruptions and their associated operational and financial risks to be their single most pressing concern (Craighead et al., 2007). Risk management in supply chain cannot be equated to disaster response. Rather, it means keeping an increasingly complex process moving efficiently at the lowest total cost and without compromising the quality of the product or customer satisfaction (Hauser, 2003). Supply chain risk management (SCRM) is defined as “the process of risk mitigation achieved through collaboration, co-ordination and application of risk management tools among the partners, to ensure continuity coupled with long term profitability of the supply chain” (Faisal et al., 2007a). SCRM is still a fairly new field of research and studies related to the topic are scarce (Ojala and Hallikas, 2006; Jüttner, 2005). It should also be noted that risks cannot be completely eliminated from supply chains but strategies can be developed to manage these risks if the dynamics between the variables related to risks in a supply chain are understood (Faisal et al., 2006).
It is important for supply chain managers to recognize that in taking action to reduce known risks, they are changing the risk profile for that organization and for others in the network (Peck, 2005). Thus, for mitigating risk in supply chains it is required to expend the risk management focus from the companies’ own sites to suppliers and sub-suppliers. There is a need to work together in risk identification, assessment, management and business continuity planning and also of formal assessment of how suppliers are working with those issues and by putting requirements into contracts (Normann and Jansson, 2004). Risk management skills which includes, awareness of risk signals, developing risk management plans, and improving end to end information visibility are essential requirements for supply chain management success (Giunipero and Pearcy, 2000; Christopher and Lee, 2004). While revisiting single-sourcing decisions and changing inventory management policies will likely help maintain continuity during future crises, experts have clearly demonstrated, and logistics managers have candidly admitted, that firms need to vastly improve their disaster management planning for managing risk in supply chains (Hale and Moberg, 2005).

4.2.3 Supply Chain Risk Mitigation Strategies

A risk management system is basically an action plan that specifies which risks can be addressed, and how to address them (Shi, 2004). Elkins et al. (2005) suggest 18 best practices to mitigate supply chain risks. Companies may not need to implement all 18 of the best practices to improve supply chain risk management capabilities. Rather, they should prioritize these 18 best practices as some of these actions can be taken with a minimal level of investment and should yield immediate benefits. There should be a plan that identifies the short-term actions that can be deployed with a minimum of investment and establish a roadmap for deploying intensive project-team resources, business intelligence systems, and improved supply chain infrastructure. SAM framework (Kleindorfer and Saad, 2005) for supply chain risk management comprise three main tasks that have to be practiced continuously and concurrently as the foundation of disruption risk management. The three tasks are: Specifying sources of risk and vulnerabilities, Assessment, and Mitigation (SAM). Further, to implement the three SAM tasks introduced above, the authors have formulated a set of 10 principles, derived from the industrial risk management and supply chain literatures. Table 4.1 summarizes nine different robust supply chain strategies that aim to improve a firm’s capability to better manage supply and/or demand under normal circumstances and to enhance a firm’s capability to sustain its operations under risk (Tang, 2006).

With so many related risks and risk-mitigation approaches to consider, managers must do two things when they begin to construct a supply-chain risk management strategy. First, they must create a shared, organization-wide understanding of supply-chain risk. Then they must determine how to adapt general risk-mitigation approaches to the circumstances of their particular company. Managers can achieve
Table 4.1  Risk mitigation strategies in supply chains

| Robust Supply Chain Strategy | Main Objective                  | Benefit(s) under normal circumstances                                      | Benefit(s) after a major disruption                      |
|------------------------------|---------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------|
| Postponement                 | Increases product flexibility    | Improves capability to manage supply                                           | Enables a firm to change the configuration of different products quickly |
| Strategic Stock              | Increases product availability  | Improves capability to manage supply                                           | Enables a firm to respond to market demand quickly during a major disruption |
| Flexible Supply Base         | Increases supply flexibility     | Improves capability to manage supply                                           | Enables a firm to shift production among suppliers promptly |
| Make-and-Buy                 | Increases supply flexibility     | Improves capability to manage supply                                           | Enables a firm to shift production between in-house production facility and suppliers rapidly |
| Economic Supply Incentives   | Increases product availability  | Improves capability to manage supply                                           | Enables a firm to adjust order quantities quickly         |
| Flexible Transportation      | Increases flexibility in transport | Improves capability to manage supply                                          | Enables a firm to change the mode of transportation rapidly |
| Revenue Management           | Increases control of product demand | Improves capability to manage demand                                          | Enables a firm to influence the customer product selection dynamically |
| Dynamic Assortment Planning  | Increases control of product demand | Improves capability to manage demand                                          | Enables a firm to influence the demands of different products quickly |
| Silent Product Rollover      | Increases control of product exposure to customers | Improves capability to manage supply and demand                           | Enables a firm to manage the demands of different products swiftly |

Adapted from Tang (2006)

the former through stress testing and the latter through tailoring risk management approaches (Chopra and Sodhi, 2004).

4.3 Supply Chain Risks Taxonomy

Supply chain structure is made up of interdependent parts that come together to provide the required products and services to the satisfaction of the customers.
Tied closely to this interdependence is the role of uncertainty within the supply chain (Sounderpandian et al., 2008). The literature in the risk management field indicates that the primary sources of risk to the business organization may be categorized into exogenous and endogenous (Ritchie and Brindley, 2000). In a supply chain, risks can be classified into two types: risks arising from within the supply chain network and risks external to it. For the former, the attributes are due to the interaction between firms across the entire supply chain network. This set of internal risks can encompass supply risk, demand risk, and trade credit risk for instance. External risks, on the other hand, arise from the interactions between the supply chain network and its environment, such as international terrorism, and natural disasters like SARS (Goh et al., 2007). Jüttner et al. (2002) suggest organizing risk sources relevant for supply chains into three categories: external to the supply chain, internal to the supply chain, and network related.

Following Cavinato (2004), Spekman and Davis (2004), and Jüttner (2005) risks in supply chains are classified under four sub-chains, physical, financial, informational, and relational. Physical sub-chain, represent traditionally viewed logistics, in the form of transportation, warehousing, handling, processing, manufacturing, and other forms of utility activities. Financial sub-chain working in parallel deals with the supply chain’s flow of money while informational sub-chains parallel the physical and financial chains through the processes and electronic systems used for creating events and triggered product movements and service mobilization. Relational sub-chains relate to the chosen linkages between buyers, sellers, and logistics parties in between them.

### 4.3.1 Risks in Physical Sub-Chain

Risks in the actual movements and flows within and between firms, transportation, service mobilization, delivery movement, storage, and inventories can be termed as the risk in physical flow of the supply chain (Cavinato, 2004). Traditionally, most of the earlier definitions of risk in supply chains found in literature took only the physical flow of goods into consideration (Spekman and Davis, 2004). Many of the risk in the physical flow are difficult to anticipate and consequently formal risk management approaches fails to mitigate them. Prominent among this class are those risk which have a low probability of occurrence but high impact like disruption risks. Supplier capacity constraint is a form of risk in physical sub-chain. Constraints exist that restrict a supplier’s ability to make rapid changes to varying demands (Zsidisin et al., 2000). Risk in physical sub-chain can also exist in form of fluctuations of demand, such as those caused by the “bullwhip effect” and may tax a supplier beyond its abilities. A supplier may not have extra equipment, available employees, or the ability to obtain necessary inputs to handle rapid spurts in demand. On the other hand, it may also be difficult for suppliers to utilize excess “slack” during order declines, which makes it difficult to attain profits from excess capacity. Phys-
ical sub-chain is also impacted by quality-related risks that can cause significant detrimental effects on the purchasing organization, with a cascading effect through the supply chain to the final consumers. Each link within a supply chain is dependent on the other links to meet product or service requirements. Quality failures can stem from the failure of suppliers to maintain capital equipment, lack of supplier training in quality principles and techniques, and damage that occurs in transit (Zsidisin et al., 2000). Risks in physical sub-chain may be further classified as shown Table 4.2.

Table 4.2 Categories of risk in physical sub-chain

| SN | Type of risk                  | Reference(s)                                | Remarks                                                                 |
|----|------------------------------|----------------------------------------------|-------------------------------------------------------------------------|
| 1  | Delays (DL)                  | Chopra and Sodhi (2004)                      | Due to high utilization or another cause of inflexibility of suppliers |
| 2  | Disruptions (DS)             | Chopra and Sodhi (2004); Finch (2004); Johnson (2001); Hale and Moberg (2005); Peck (2005) | Very unpredictable but of high impact.                                  |
| 3  | Supplier capacity constraints (CC) | Zsidisin et al. (2000); Giunipero and Eltantawy (2004) | Unable to handle sudden spurt or to utilize excess slack                |
| 4  | Production technological changes (TC) | Zsidisin et al. (2000); Giunipero and Eltantawy (2004) | Supplier not able to produce items to necessary demand level and at a competitive price |
| 5  | Transportation (TR)          | Cavinato (2004); Speckman and Davis (2004); Svensson, (2004); Peck (2005) | Pertinent in case of logistics outsourcing as is the case of 3PL         |
| 6  | Inventory (IN)               | Chopra and Sodhi (2004)                      | Excess inventory for products with high value or short life cycles can get expensive |
| 7  | Procurement (PR)             | Hallikas et al. (2002); Chopra and Sodhi (2004) | Unanticipated increases in acquisition costs                           |
| 8  | Capacity Inflexibility (CI)  | Chopra and Sodhi (2004); Johnson (2001); Giunipero and Eltantawy (2004); Svensson (2004) | Facility fails to respond to changes in demand                          |
| 9  | Design (DG)                  | Zsidisin et al. (2000); Speckman and Davis (2004) | Suppliers’ inability to incorporate design changes                      |
| 10 | Poor quality (PQ)            | Treleven and Schweikhart (1988); Zsidisin et al. (2000); Svensson (2004); Sounderpandian et al. (2008) | If suppliers plants don’t have quality focus                            |
4.3.2 Risks in Financial Sub-Chain

Risks in supply chains due to the flows of cash between organizations, incurrence of expenses, and use of investments for the entire chain/network, settlements, A/R (accounts receivables) and A/P (accounts payables) processes and systems can be classified under financial risks. Financial risks also include factors like settlement process disruption, improper investments, and not bringing cost transparency to the overall supply chain (Cavinato, 2004). In case of strategic alliances the risk of financial stability of alliance partners is crucial for supply chain success (Giunipero and Eltantawy, 2004). According to Peck (2005), managing risks in financial sub-chain is not an easy task as disruptions due to macroeconomic vacillations like currency fluctuations or due to strained relations among nations are difficult to predict and are beyond the direct control of supply chain managers and business strategists.

A better understanding of the causal relationship between supply chain performance and financial measures is critical to both supply chain and financial managers (Tsai, 2008). Financial risks can also present themselves through the risk of re-working stock and penalties for non-delivery of goods (Christopher and Lee, 2004). When a firm has operations in multiple countries, changes in foreign exchange rates can have a significant impact on both the income statement and the balance sheet. Price changes for commodities such as oil and electricity can have an impact on supply chain costs and price changes for commodities like steel and copper can affect the cost of goods sold. Labor-intensive enterprises in many developing countries have felt great pressure from the rise of labor-related costs, such as wages and costs to improve working conditions. A January 2006 report by American Chamber of Commerce in China found that rising labor costs significantly decreased margins in 48% of U.S. manufacturers in China (Jiang et al., 2007). Changing economic scenario in key markets are also a major source of risk in financial sub-chain e.g. recent recession in US economy has severely dented the profit margins of many of the firms in India that used to have major chunk of their products being exported to US markets. Major risks in financial sub-chain are represented in Table 4.3.

4.3.3 Risks in Relational Sub-Chain

This dimension of risk concerns the degree of interdependence among partners and the tendency of a partner to act in its own self interest to the detriment of other supply chain members (Spekman and Davis, 2004). Supply chains are entities of interdependent parts which come together to provide the product/service to the final customer. The type of the relationship is likely to have an effect on the supply chain risks (Ojala and Hallikas, 2006). Though in supply chain literature long term collaborative relationships are recommended (Mentzer et al., 2000; Barratt and Oliveira, 2001; Callioni and Billington, 2001), companies particularly SMEs competing on the basis of low cost depend on short term cost based relationships with their part-
| SN | Type of risk                         | Reference(s)                     | Remarks                           |
|----|------------------------------------|----------------------------------|-----------------------------------|
| 1  | Cost/price risk (CR)               | Treleven and Schweikhart (1988); Zsidisin et al. (2000) | Concerns competitive cost risk    |
| 2  | Business risks (BR)                | Zsidisin et al. (2000)           | Concerns financial stability of the supplier |
| 3  | Fiscal risks (FR)                  | Harland et al. (2003)            | Arises through changes in taxation |
| 4  | Untimely payments (UT)             | Speckman and Davis (2004); Shi (2004) | Loss of goodwill and may impact much on SMEs |
| 5  | Settlement process disruption (SP)  | Cavinato (2004)                  | Leads to delay in payments and impacts SC profitability |
| 6  | Volatile oil prices (OP)           | Faisal et al. (2006)             | Impacts inbound and outbound costs |
| 7  | Lack of hedging (LH)               | Speckman and Davis (2004)        | Disastrous in case of bankruptcy of partners in the SC |
| 8  | Investment risks (IR)              | Hallikas et al. (2002); Ojala and Hallikas (2006) | Caused by economic fluctuations in the market |
| 9  | Unstable pricing (UP)              | Speckman and Davis (2004)        | May lead to lack of trust among SC partners |
| 10 | Exchange rate risks/ currency fluctuations (ER) | Chopra and Sodhi (2004); Peck (2005) | Impacts the procurement strategy of the firm |

In cost based relationships the firms do not share information and partners are switched frequently thus giving rise to risks in relational sub-chains as enunciated below.

### 4.3.3.1 Reputational Risk (RR)

Outsourcing from low cost destinations is fraught with dangers of associated risks arising from moral issues like child labor, labor health, safety, and welfare in developing countries. Consumers are shunning products that contain materials manufactured under sweatshop labor conditions (Jiang et al., 2007). The cases of labor abuse in the sporting goods and apparel industry, recent being that of Primark show that such negative publicity can damage brands and erode market positions substantially (Zadek, 2004; Harland et al., 2003; Frenkel and Scott, 2002).
4.3.3.2 Lack of Trust and Opportunism Risk (TOR)

One of the most important factors affecting the entire process of supply chain management is the trust among the trading partners (Sinha et al., 2004). Trust may concern a partner’s willingness to perform according to agreements, or the intention to do so. Risks exist if the party is not competent to act or if the party chooses not to act (Spekman and Davis, 2004). Lack of trust may also lead to opportunism, where one supply chain partner acts in its own self-interest to the detriment of others.

4.3.3.3 Legal Risk (LR)

These risks expose the firms to litigation with action arising from customers, suppliers, shareholders, and employees (Harland et al., 2003).

4.3.3.4 Intellectual Property Rights Risk (IPR)

Increased reliance on outsourcing creates a loss of control and a risk of losing proprietary information shared between parties (Giunipero and Eltantawy, 2004). If there are no predefined rules and the organizations are not careful regarding the dissemination of information to its suppliers, the probability of losing the proprietary information is high. Today suppliers may work for different organizations at the same time and in general the enforcement mechanisms related to intellectual property are weak in many developing countries and thus there is a risk that proprietary information may be leaked to competitors.

4.3.4 Risks in Informational Sub-Chain

Risks associated with materials flows are not unrelated to the risks associated with information flows. Orders that are transmitted incorrectly, a lack of transparency and visibility in the supply chain, or hesitancy in sharing accurate and timely information with partners, all contribute to a supply chain’s inability to perform as intended (Spekman and Davis, 2004). So based on the type of impact that different information risks have on the supply chain, they can be broadly classified as (Faisal et al., 2007b):

4.3.4.1 Information Security/Breakdown Risks (SR)

Today computer based information systems are central to the supply chain and thus their failure can result in a substantial cost. In general this cost can be immediate lost sales, emergency service cost, cost of restoring data, and long-term loss of customer goodwill (Cardinali, 1998). Security is defined as the protection of data against accidental or intentional disclosure to unauthorized persons, or unauthorized modifications or destruction. It is a careful balance between information safeguard and user
access (McFadden, 1997). Information security risks arise from hackers, viruses and worms, distributed denial of service attacks or even the internal employee frauds of the organization. Terrorist attacks like 9/11 and natural disasters like Hurricanes, Tsunami have made organizations to rethink their information security strategies.

### 4.3.4.2 Forecast Risks (FR)

Forecast risks results from a mismatch between a company’s projections and actual demand (Chopra and Sodhi, 2005). All kinds of information distortions in a supply chain, often lead to the risks of bullwhip (Piplani and Fu, 2005). It creates situations where the orders to the supplier tend to have larger fluctuations than sales to the customer.

### 4.3.4.3 Information Systems/Information Technology Outsourcing Risk (OR)

IS/IT outsourcing is broadly defined as a decision taken by an organization to contract-out or sell the organization’s IT assets, people and/or activities to a third party supplier, who in exchange provides and manages assets and services for monetary returns over an agreed time period (Kern and Willcocks, 2000). IT outsourcing risks include opportunism by vendors, hidden costs, loss of control, poaching, and information security apprehensions.

### 4.4 Methodology

The analytic hierarchy process (AHP) developed by Saaty (1980) is a multi-criteria decision-making tool that can handle unstructured or semi-structured decisions with multi-person and multi-criteria inputs. It also allows users to structure complex problems in the form of a hierarchy or a set of integrated levels. In addition to this, AHP is easier to understand and can effectively handle both qualitative and quantitative data (Durán and Aguilo, 2008). The AHP attracted the interest of many researchers for long because of its easy applicability and interesting mathematical properties (Sasamal and Ramanjaneyulu, 2008). AHP involves the principles of decomposition, pair wise comparisons, and priority vector generation and synthesis.

Though the purpose of AHP is to capture the expert’s knowledge, the conventional AHP still cannot reflect the human thinking style. In spite of its popularity, this method is often criticized because of a series of pitfalls associated with the AHP technique which can be summarized as follows (Durán and Aguilo, 2008):

- Its inability to adequately handle the inherent uncertainty and imprecision associated with the mapping of the decision-maker’s perception to exact numbers.
- In the traditional formulation of the AHP, human’s judgments are represented as exact (or crisp, according to the fuzzy logic terminology) numbers. However, in many practical cases the human preference model is uncertain and decision-
makers might be reluctant or unable to assign exact numerical values to the comparison judgments.

- Although the use of the discrete scale of 1–9 has the advantage of simplicity, the AHP does not take into account the uncertainty associated with the mapping of one’s judgment to a number.

A good decision-making models needs to tolerate vagueness or ambiguity since fuzziness and vagueness are common characteristics in many decision-making problems (Yu, 2002). Due to the fact that uncertainty should be considered in some or all of the pairwise comparison values, the pairwise comparison under traditional AHP, which needs to select arbitrary values in the process, may not be appropriate (Yu, 2002). Thus the use of fuzzy numbers and linguistic terms may be more suitable, and the fuzzy theory in AHP should be more appropriate and effective than traditional AHP in an uncertain pairwise comparison environment (Kang and Lee, 2007). Fuzzy set theory bears a resemblance to the logical behavior of human brain when faced with imprecision (Cakir and Canbolat, 2008). It has the advantage of mathematically representing uncertainty and vagueness and provides formalized tools for dealing with the imprecision intrinsic to many problems (Chan and Kumar, 2007).

Although the purpose of the original AHP was to capture expert knowledge, conventional AHP did not truly reflect human cognitive processes-especially in the context of problems that were not fully defined and/or problems involving uncertain data (so-called “fuzzy” problems) (Fu et al., 2006). Laarhoven and Pedrycz (1983) therefore introduced the concept of “fuzzy theory” to AHP assessments. This so-called “fuzzy analytic hierarchical process” (fuzzy AHP) was able to solve uncertain “fuzzy” problems and to rank excluded factors according to their weight ratios. The research presented in this chapter prefers Chang’s extent analysis method (Chang 1992, 1996) since the steps of this approach are relatively easier than the other fuzzy AHP approaches and similar to the conventional AHP (Büyüközkan et al., 2008; Bozbura et al., 2007; Büyüközkan, 2008; Chan and Kumar, 2007). Fuzzy-AHP has been widely used for prioritization purposes like prioritization of organizational capital (Bozbura and Beskese, 2007), key capabilities in technology management (Erensal et al., 2006), prioritization of human capital measurement indicators (Bozbura et al., 2007), adoption of electronic marketplaces (Fu et al., 2006), and supply base reduction (Sarkar and Mohapatra, 2006).

A fuzzy number is a special fuzzy set \( F = \{ x \in R | \mu_F(x) \} \), where \( x \) takes its values on the real line \( R_1 : -\infty < x < +\infty \) and \( \mu_F(x) \) is a continuous mapping from \( R_1 \) to the close interval \([0, 1]\). A triangular fuzzy number can be denoted as \( M = (l, m, u) \). Its membership function \( \mu_M(x) : R \rightarrow [0, 1] \) is equal to:

\[
\mu_M(x) = \begin{cases} 
0, & x < l \text{ or } x > u, \\
(x-l)/(m-l), & l \leq x < m, \\
(x-u)/(m-u), & m \leq x \leq u. 
\end{cases}
\]

(4.1)

Where \( l \leq m \leq u \), \( l \) and \( u \) stand for the lower and upper value of the support of \( M \), respectively, and \( m \) is the mind-value of \( M \). When \( l = m = u \), it is a non fuzzy number by convention. The main operational laws for two triangular fuzzy numbers
\( M_1 \) and \( M_2 \) are as follows (Kauffman and Gupta, 1991):
\[
M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) , \\
M_1 \otimes M_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2) , \\
\lambda \otimes M_1 = (\lambda l_1, \lambda m_1, \lambda u_1), \lambda > 0, \lambda \\
M_1^{-1} \approx (1/u_1, 1/m_1, 1/l_1) .
\] (4.2)

Let \( X = \{x_1, x_2, \ldots, x_n\} \) be an object set, and \( U = \{u_1, u_2, \ldots, u_m\} \) be a goal set. According to the method of Chang’s extent analysis model, each object is taken and extent analysis for each goal, \( g_i \), is performed respectively (Chang, 1992, 1996). Therefore, \( m \) extent analysis values for each object can be obtained with the following signs:
\[
M_{g_i}^1, M_{g_i}^m, i = 1, 2, \ldots, n .
\] (4.3)

Where all the \( M_{g_i}^j(j = 1, 2, \ldots, m) \) are triangular fuzzy numbers. A triangular fuzzy number can be denoted as \( M = (l, m, u) \) where \( l \leq m \leq u \), \( l \) and \( u \) stand for the lower and upper value of the support of \( M \), respectively, and \( m \) is the mid-value of \( M \).

The steps of the improved Chang’s extent analysis model, which is applied in this chapter, can be given as follows:

Step 1: The value of fuzzy synthetic extent with respect to the \( i \)th object is defined as:
\[
S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} .
\] (4.4)

To obtain \( \sum_{j=1}^{m} M_{g_i}^j \), perform the fuzzy addition operation of \( m \) extent analysis values for a particular matrix such that
\[
\sum_{j=1}^{m} M_{g_i}^j = \left( \sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \] (4.5)

and to obtain \( \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \), perform the fuzzy addition operation of \( M_{g_i}^j(j = 1, 2, \ldots, m) \) values such that
\[
\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left( \sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \] (4.6)
and then compute the inverse of the vector in (4.6) such that

$$\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_{ij}} \right]^{-1} = \begin{pmatrix} \frac{1}{n} \sum_{i=1}^{n} u_i & \frac{1}{n} \sum_{i=1}^{n} m_i & \frac{1}{n} \sum_{i=1}^{n} l_i \end{pmatrix}.$$  \hspace{1cm} (4.7)

The principles for the comparison of fuzzy numbers were introduced to derive the weight vectors of all elements for each level of the hierarchy with the use of fuzzy synthetic values. We now discuss these principles that allow the comparison of fuzzy numbers. (Zhu et al., 1999).

Step 2: The degree of possibility of \( M_2 \geq M_1 \) is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[ \min \left( \mu_{M_1}(x), \mu_{M_2}(y) \right) \right],$$  \hspace{1cm} (4.8)

where \( \sup \) represents supremum (i.e., the least upper bound of a set) and when a pair \((x, y)\) exists such that \( y \geq x \) and \( \mu_{M_1}(x) = \mu_{M_2}(y) \), then we have \( V(M_2 \geq M_1) = 1 \).

Since \( M_1 = (l_1, m_1, u_1) \) and \( M_2 = (l_2, m_2, u_2) \) are convex fuzzy number it follows that:

$$V(M_2 \geq M_1) = \text{hgt}(M_1 \cap M_2) = \mu_{M_2}(d)$$

(where the term hgt is the height of fuzzy numbers on the intersection of \( M_1 \) and \( M_2 \))

$$\mu_{M_2}(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_1 \geq u_2 \\ \frac{l_2-u_2}{(m_1-u_2)-(m_1-l_1)}, & \text{otherwise} \end{cases}.$$  \hspace{1cm} (4.9)

Where \( d \) is the crossover point’s abscissa of \( M_1 \) and \( M_2 \). To compare \( M_1 \) and \( M_2 \), we need both the values of \( V(M_1 \geq M_2) \) and \( V(M_2 \geq M_1) \).

Step 3: The degree of possibility for a convex fuzzy number to be greater than \( k \) convex fuzzy numbers \( M_i \) \((i = 1, 2, \ldots, k)\) can be defined by

$$V(M_2 \geq M_1, M_2, \ldots, M_k) = V[(M \geq M_1) \text{ and } M \geq M_2 \text{ and } \ldots \text{ and } (M \geq M_k)] = \min V(M \geq M_i), \quad i = 1, 2, 3, \ldots, k$$

Assume that

$$d'(A_i) = \min V(S_i \geq S_k),$$  \hspace{1cm} (4.10)

for \( k = 1, 2, \ldots, n; k \neq i \). Then the weight vector is obtained as follows:

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T.$$  \hspace{1cm} (4.11)

Where \( A_i \) \((i = 1, 2, \ldots, n)\) are \( n \) elements.

Step 4: After normalization, the normalized weight vectors are,

$$W = (d(A_1), d(A_2), \ldots, d'(A_n))^T.$$  \hspace{1cm} (4.12)

Where \( W \) is not a fuzzy number.


### 4.4.1 A Numerical Application

As previously mentioned, in the third step of the framework, fuzzy AHP methodology is applied for weight determination. The sub-chains together with related risks are represented in Fig. 4.1.

In order to perform a pairwise comparison among the requirements, the linguistic scale as proposed by Büyüközkan (2008) and Büyüközkan et al. (2008) is adopted in this chapter. The scale is depicted in Fig. 4.2 and the corresponding explanations are provided in Table 4.4. Figure 4.2 shows the triangular fuzzy numbers $M = (l, m, u)$ where $l \leq m \leq u$, $l$ and $u$ stand for the lower and upper value of the support of $M$, respectively, and $m$ is the mid-value of $M$. Similar to the importance scale defined in Saaty’s classical AHP (Saaty, 1980), five main linguistic terms are used to compare the criteria: “equal importance (EI)”, “moderate importance (MI)”, “strong importance (SI)”, “very strong importance (VSI)” and “demonstrated importance (DI)”. Further, their reciprocals: “equal unimportance (EUI)”, “moderate unimportance (MUI)”, “strong unimportance (SUI)”, “very strong unimportance (VSUI)” and “demonstrated unimportance (DUI)” have also been considered. For instance, if criterion A is evaluated “strongly important” than criterion B, then this answer means that criterion B is “strongly unimportant” than criterion A.

![Fig. 4.1 A hierarchy based model of supply chain risks](image-url)
The proposed model was evaluated for small and medium enterprises (SMEs) cluster. A group of experts consisting of academics and professionals were asked to make pairwise comparisons for the sub-chains and their related risks mentioned in Sect. 4.5. A questionnaire (see Appendix A) is provided to get the evaluations. The overall results could be obtained by taking the geometric mean of individual
evaluations. However, since the group of experts came up with a consensus by the help of the Delphi Method in this case, a single evaluation could be obtained to represent the group’s opinion (Bozbura et al., 2007; Büyüközkan, 2008) as represented in Table 4.5 for relative importance of sub-chain risks.

The values of fuzzy synthetic extents with respect to the sub-chain are calculated by applying formula (4.1) as below

\[
R_{PSC} = (3.5, 4.66, 6) \times (0.0428, 0.0577, 0.0762) = (0.1498, 0.2688, 3.4572),
\]
\[
R_{FSC} = (4.5, 6, 7.5) \times (0.0428, 0.0577, 0.0762) = (0.1926, 0.3462, 0.5715),
\]
\[
R_{RSC} = (2.66, 3.66, 5.5) \times (0.0428, 0.0577, 0.0762) = (0.1138, 0.2111, 0.4191),
\]
\[
R_{ISC} = (2.46, 3, 4.33) \times (0.0428, 0.0577, 0.0762) = (0.1052, 0.1731, 0.3299).
\]

The degrees of possibility are calculated using these values and formula (4.5) as below:

\[
V(R_{PSC} \geq R_{FSC}) = 0.1926 - 0.4572/(0.2688 - 0.4572) - (0.3462 - 0.1926) = 0.7736,
\]
\[
V(R_{PSC} \geq R_{RSC}) = 1.00,
\]
\[
V(R_{PSC} \geq R_{ISC}) = 1.00,
\]
\[
V(R_{FSC} \geq R_{PSC}) = 1.00,
\]
\[
V(R_{FSC} \geq R_{RSC}) = 1.00,
\]
\[
V(R_{FSC} \geq R_{ISC}) = 1.00,
\]
\[
V(R_{RSC} \geq R_{PSC}) = 0.1498 - 0.4191/(0.2111 - 0.4191) - (0.2688 - 0.1498) = 0.8235,
\]
\[
V(R_{RSC} \geq R_{FSC}) = 0.1926 - 0.4191/(0.2111 - 0.4191) - (0.3462 - 0.1926) = 0.3289,
\]
\[
V(R_{RSC} \geq R_{ISC}) = 1.00,
\]
\[
V(R_{ISC} \geq R_{PSC}) = 0.1498 - 0.3299/(0.1731 - 0.3299) - (0.2688 - 0.1498) = 0.6530,
\]
\[
V(R_{ISC} \geq R_{FSC}) = 0.1926 - 0.3299/(0.1731 - 0.3299) - (0.3462 - 0.1926) = 0.4423,
\]
\[
V(R_{ISC} \geq R_{RSC}) = 0.1138 - 0.3299/(0.1731 - 0.3299) - (0.2111 - 0.1138) = 0.8504.
\]
The weight vector of the main factors of the hierarchy can be calculated by using the formulas (4.10) and (4.6) as below:

\[
\begin{align*}
    d'(\text{PhysicalSC}) &= V(R_{PSC} \geq R_{FSC}, R_{RSC}, R_{ISC}) \\
    &= \min(0.7736, 1, 1) = 0.7736, \\
    d'(\text{FinancialSC}) &= V(R_{FSC} \geq R_{PSC}, R_{RSC}, R_{ISC}) \\
    &= \min(1, 1, 1) = 1, \\
    d'(\text{RelationalSC}) &= V(R_{RSC} \geq R_{PSC}, R_{FSC}, R_{ISC}) \\
    &= \min(0.8235, 0.3289, 1) = 0.3289, \\
    d'(\text{InformationalSC}) &= V(R_{ISC} \geq R_{PSC}, R_{FSC}, R_{ISC}) \\
    &= \min(0.6530, 0.4423, 0.8504) = 0.4423, \\
    W' &= (0.7736, 1, 0.3289, 0.4423)^T.
\end{align*}
\]

Hence, via normalization, the normalized vectors of Physical, Financial, Relational, and Informational sub-chains risks are obtained as below:

\[
    W_{\text{objective}} = (0.3039, 0.3929, 0.1292, 0.1738)^T
\]

In a similar way, the importance weights of the risks within physical sub-chain are calculated as follows

\[
    W = (d(DL), d(DS), d(CC), d(TC), d(TR), d(IN), d(PR), d(CI), d(DG), d(PQ))^T \\
    W_{\text{Physical}} = (0.1123, 0.0679, 0.1231, 0.0697, 0.1298, 0.0753, 0.0526, 0.1336, 0.0579, 0.1666)^T.
\]

It is observed that for the physical sub-chain poor quality, capacity inflexibility, transportation risks, product technological changes are more important than other risks.

In a similar way, the importance weights of the risks within financial sub-chain are calculated as follows

\[
    W = (d(CR), d(BR), d(FR), d(UT), d(SP), d(OP), d(LH), d(IR), d(UP), d(ER))^T, \\
    W_{\text{Financial}} = (0.1121, 0.0893, 0.0547, 0.1443, 0.0582, 0.1204, 0.1318, 0.0357, 0.1158, 0.1377)^T.
\]

It can be concluded that for financial sub-chain untimely payments, lack of hedging, and volatile oil prices emerge as the most important risks. In a similar way, the
importance weights of the risks within relational sub-chain are calculated as follows

\[ W = (d(\text{RR}), d(\text{TOR}), d(\text{LR}), d(\text{IPR}))^T, \]

\[ W_{\text{Relational}} = (0.2881, 0.2493, 0.2712, 0.1924)^T. \]

For relational sub-chain, reputational risks and lack of trust and opportunism risk seem to appear more important than other risks. In a similar way, the importance weights of the risks within informational sub-chain are calculated as follows

\[ W = (d(\text{SR}), d(\text{FR}), d(\text{OR}))^T, \]

\[ W_{\text{Informational}} = (0.3799, 0.3761, 2.440)^T. \]

It can be concluded that for informational sub-chain forecast risks emerges as the most important risk.

Finally, considering the obtained results, composite priority weights for supply chain risks can be calculated as given in Table 4.6.

| Sub-chain | Local weights | Sub-chain risks | Local weights | Global weights |
|-----------|---------------|-----------------|---------------|----------------|
| Physical  | 0.3039        | DL 0.1123       | 0.0341        |                |
|           |               | DS 0.0679       | 0.0206        |                |
|           |               | CC 0.1231       | 0.0374        |                |
|           |               | TC 0.0697       | 0.0212        |                |
|           |               | TR 0.1298       | 0.0394        |                |
|           |               | IN 0.0753       | 0.0229        |                |
|           |               | PR 0.0526       | 0.0159        |                |
|           |               | CY 0.1336       | 0.0406        |                |
|           |               | DG 0.0579       | 0.0176        |                |
|           |               | PQ 0.1666       | 0.0506        |                |
| Financial | 0.3929        | CR 0.1121       | 0.0440        |                |
|           |               | BR 0.0893       | 0.0351        |                |
|           |               | FR 0.0547       | 0.0215        |                |
|           |               | UT 0.1443       | 0.0567        |                |
|           |               | SP 0.0582       | 0.0229        |                |
|           |               | OP 0.1204       | 0.0473        |                |
|           |               | LH 0.1318       | 0.0518        |                |
|           |               | IR 0.0357       | 0.0140        |                |
|           |               | UP 0.1158       | 0.0455        |                |
|           |               | ER 0.1377       | 0.0541        |                |
| Relational| 0.1292        | RR 0.2881       | 0.0372        |                |
|           |               | LR 0.2493       | 0.0322        |                |
|           |               | TOR 0.2712      | 0.0350        |                |
|           |               | IPR 0.1924      | 0.0248        |                |
| Informational | 0.1738 | SR 0.3799       | 0.0660        |                |
|           |               | FR 0.3761       | 0.0653        |                |
|           |               | OR 0.2440       | 0.0424        |                |
Based on the values in Table 4.6 it can be concluded that forecast risks, system breakdown/security risks, untimely payment risks, exchange rate risks, lack of hedging risks, quality risks are the most important risks in supply chains as perceived by small and medium enterprises.

4.5 Concluding Remarks

A very important task in risk management is to establish those risk factors that are important to a particular company. With the help of this assessment the company is able to focus its resources more efficiently. The model presented in this chapter would help the practitioners to assign relative importance to various risks in a supply chain and develop plans accordingly to mitigate them.

Despite the recent surge in academic and practitioner publications regarding supply chain risks, the research presented in this chapter provides an additional value to the body of knowledge and consequently to managerial decision making. Because of the subjective and intangible nature of the risk variables considered in the model, the proposed methodology based on fuzzy-AHP framework provides a systematic method and is more capable of capturing a human’s appraisal of ambiguity when complex multi-attribute decision-making problems are considered.

For further research, the model developed in this chapter can be evaluated for supply chains for large corporations. Also, other fuzzy multi-attribute approaches such as fuzzy TOPSIS and fuzzy outranking methods can be used for the prioritization of supply chain risks. In future models we can also consider the interdependence among various supply chain risks and in that case analytic network process (ANP) approach that takes into account the dependence and feedback can be applied to evaluate the model.

As risk is inherent in every link within a firm’s supply chain it is impossible to completely insulate a supply chain from risks. But by understanding the sources of risk and prioritizing them, firms can take a proactive view for reducing and managing these risks.

Appendix

Sample questions from the questionnaire used to facilitate comparisons of sub-chain risks

Questionnaire

Read the following questions and put check marks on the pairwise comparison matrices. If an attribute on the left is more important than the one matching on the right, put your check mark to the left of the “Equal importance” column, under the
importance level (column) you prefer. On the other hand, if an attribute on the left is less important than the one matching on the right, put your check mark to the right of the importance “Equal Importance” column, under the importance level (column) you prefer.

Questions

With respect to the overall goal “prioritization of the supply chain risks”.

Q1. How important are physical sub-chain risks (PSR) when compared with financial sub-chain risks (FSR)?

Q2. How important are financial sub-chain risks (FSR) when compared with relational sub-chain risk (RSR)?

Q3. How important are informational sub-chain risks (ISR) when compared with financial sub-chain risks (FSR)?

Q4. How important are physical sub-chain risks (PSR) when compared with informational sub-chain risks (ISR)?

Q5. How important are physical sub-chain risks (PSR) when compared with relational sub-chain risks (RSR)?

Q6. How important are relational sub-chain risks (RSR) when compared with informational sub-chain risks (ISR)?

| Questions | Sub-chain risks | Demonstrated Importance | Very Strong Importance | Strong Importance | Moderate Importance | Equal Importance | Moderate unimportance | Strong unimportance | Very Strong unimportance | Demonstrated unimportance | Sub-chain risks |
|-----------|-----------------|--------------------------|------------------------|-------------------|---------------------|------------------|------------------------|----------------------|---------------------------|--------------------------|-----------------|
| 1         | PSR             |                          |                        |                   |                     |                  |                        |                      |                           |                          | FSR             |
| 2         | FSR             | ✓                        |                        |                   |                     |                  |                        |                      |                           |                          | RSR             |
| 3         | ISR             | ✓                        |                        |                   |                     |                  |                        |                      |                           |                          | FSR             |
| 4         | PSR             | ✓                        |                        |                   |                     |                  |                        |                      |                           |                          | ISR             |
| 5         | PSR             | ✓                        |                        |                   |                     |                  |                        |                      |                           |                          | RSR             |
| 6         | RSR             | ✓                        |                        |                   |                     |                  |                        |                      |                           |                          | ISR             |
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