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# MULTI OBJECTIVE OPTIMIZATION MODELS FOR MANAGING SUPPLY RISK IN SUPPLY CHAINS

A Thesis in

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by

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# ABSTRACT

In today’s highly competitive market, firms have to focus on their core competencies to achieve success. While enjoying the benefits of building a highly integrated supply chain, firms also expose themselves to uncertain events, which are generally called as “risks.” Considering the importance of suppliers in a supply chain, supply risk has to be managed.

This thesis first reviews supplier selection criteria and methods. Then, risks in a supply chain are discussed in detail with a summary of current research and the application of risk management in a supply chain. After defining the research questions, this thesis proposes a quantification method for supply risks. A five-step strategic supplier selection model considering risks and an optimization model for inventory, production, and transportation considering risks are developed thereafter.

The major contributions of this thesis are:

- Developed a supply risk quantification method. In order to quantify supply risks, the two components of risk, hazard and exposure, are first quantified separately and then combined either analytically or by scenario analysis. Firms can use their own historical data to build the hazard functions and the exposure functions or use the format and distributions recommended in this thesis.
- Developed a five-step multi-criteria strategic supplier selection method. Weight range with three parameters is used to determine the best possible ranking for each candidate supplier as opposed to the single weight used in the traditional AHP method. Then, different types of multi-criteria optimization models are used to present decision makers with alternatives from which to choose.
- Expanded the MTOM model from the author’s Master’s thesis to a multi-criteria optimization model considering risks. The model can handle multiple suppliers, manufacturers, retailers, components, products, transportation options, and production lines and can optimize inventory, transportation, and production simultaneously considering risks and total cost.

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# Chapter 1

# Introduction

## 1.1. Supply chain management

During the 1990s, facing challenges from increasingly demanding customers, globalization, and accelerated competition, and with the development of information technologies, many manufacturers and service providers collaborated with their suppliers to upgrade traditional supply and materials management functions and integrate them into their corporate strategy. Many wholesalers and retailers integrated their logistics functions with other functions as well to enhance competitive advantages. Eventually, these efforts evolved into a holistic and strategic approach to materials and logistics management, known as Supply Chain Management (SCM) (Tan 2002).

A supply chain consists of all the stages involved, directly or indirectly, in fulfilling a customer demand. It not only includes the manufacturers and suppliers, but also transporters, warehouses, retailers, and customer themselves (Chopra and Meindl 2001). New and Payne (1995) described SCM as the chain linking each element of the manufacturing and supply process from raw materials to the end users, and treating all firms within the supply chain as a unified virtual business entity. Harwick (1997) pointed out that SCM is a philosophy that extends traditional internal activities by embracing an inter-enterprise scope, bringing trading partners together with the goal of optimization and efficiency. Simchi-Levi et al. (2000) defined SCM as a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed in the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements. Successful SCM can provide sustainable competitive advantages to firms by improving product quality, delivery speed, service, etc. at low cost, and thus enhance customers' satisfaction levels. A survey conducted in 2003 by Accenture, INSEAD, and Stanford University showed that the importance of SCM was already realized by most responding firms and it has become more and more important to firms as a competitive differentiator (Mulani 2005). Figure 1.1 shows some results from the survey.

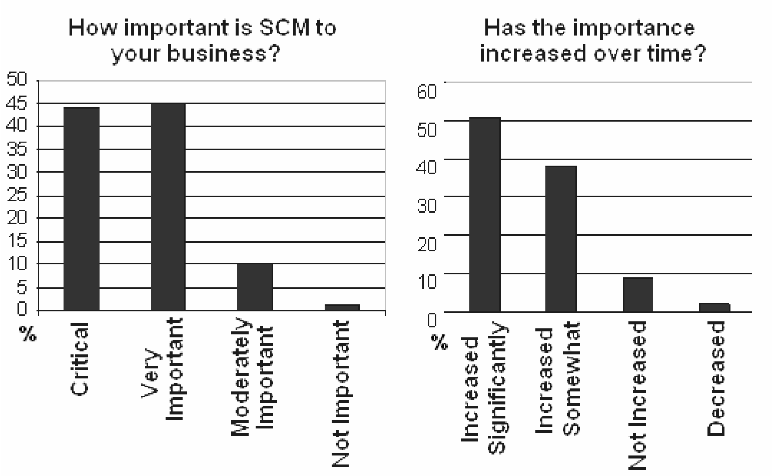


Figure 1.1 Survey results in 2003

## 1.2. Research problem genesis

Buckley et al. (1976) defined a general “framework for research methodology” as shown in Figure 1.2. It has the following six steps:

- Problem genesis
- Problem definition and statement
- Mode selection
- Strategy development
- Domain selection
- Technique decisions

Using the above framework, the factors that contributed to the development of this research are introduced in this section. Research problems are defined in section 1.3.

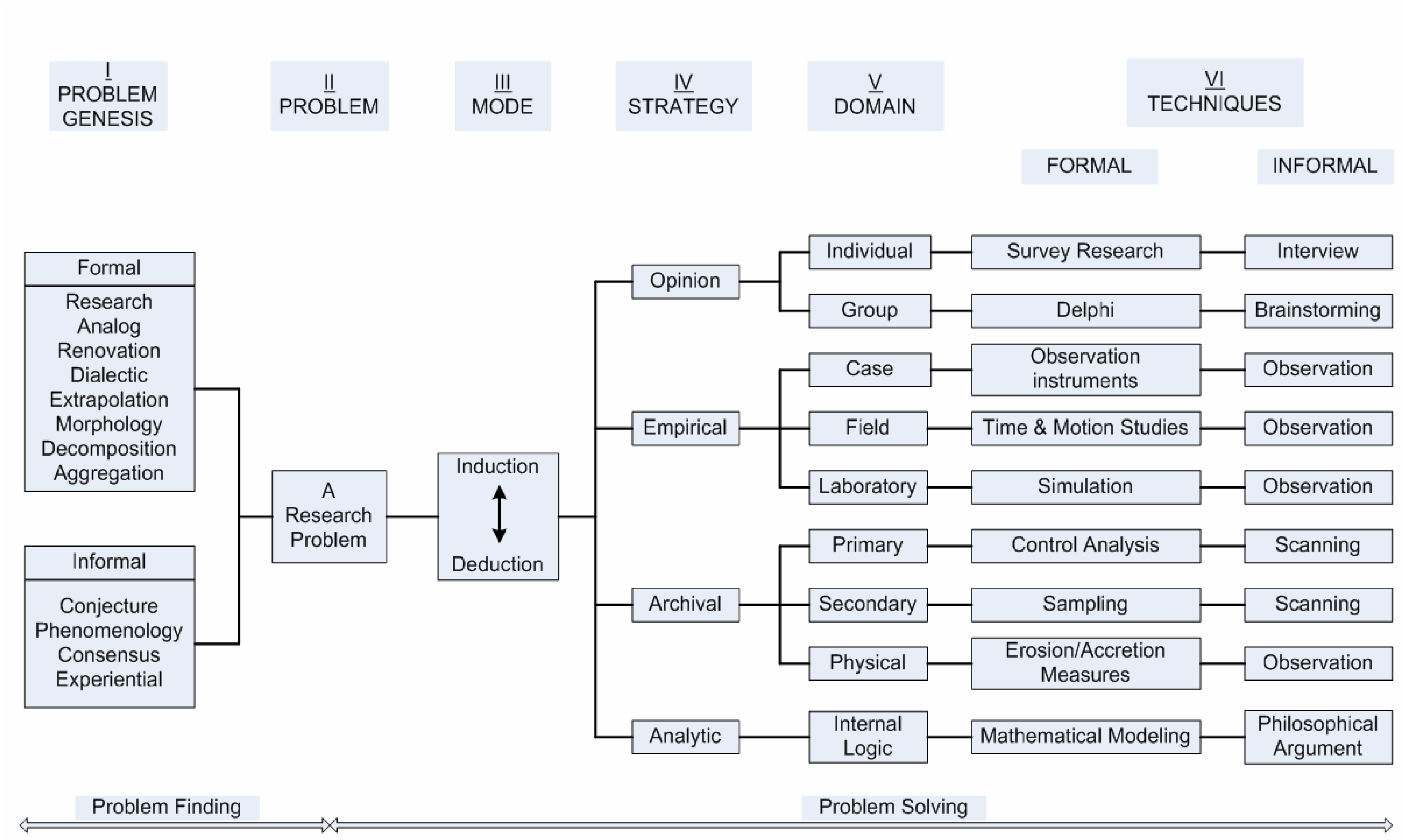


**Figure 1.2 Research framework**

### 1.2.1. Globalization

When HP sells a $1,500 laptop in Hong Kong, the buyer may actually get the memories and display screen from South Korea, the case and hard drive from Thailand, the wireless card from Malaysia, the graphics controller chip from Taiwan, the microprocessor from the United States, and have the assembly done in China.

Over the last several decades, a lot of factors have led to the increasing globalization of the world economy including improving transportation, communication, and information technologies, decreasing tariffs and international trade barriers, economic regionalism, etc. These changes have contributed to the development of a global market, which has attracted firms to extend their business overseas. Products and services have become more and more available to consumers worldwide. Table 1.1 shows the increases of merchandise imports and exports worldwide from 1993 to 2003.

Global competition is intensified because consumers have many more choices than before, and they always want to choose those firms which can offer better products and services at lower costs. Those pressures have led to increasing emphasis on the reengineering of internal business processes and working more collaboratively with business partners and customers worldwide. Successful global supply chain management has become critical for firms to maintain a competitive position internationally in increasingly dynamic markets with shorter product life cycles and greater uncertainty in customer demands.

**Table 1.1 World merchandise imports and exports by regions (1993-2003) ***

| (in million dollars) | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Imports** | | | | | | | | | | | |
| North America | 743070 | 844915 | 939900 | 997825 | 1100580 | 1151115 | 1280410 | 1504875 | 1407255 | 1428530 | 1548860 |
| Latin America | 191300 | 223700 | 252500 | 275400 | 327800 | 346100 | 332400 | 388200 | 380300 | 353900 | 366000 |
| European Union (15) | 1487610 | 1690635 | 2050935 | 2101330 | 2089635 | 2212010 | 2262500 | 2404870 | 2361115 | 2463085 | 2919570 |
| Africa | 98800 | 106600 | 126900 | 125400 | 132700 | 133000 | 128300 | 129700 | 135100 | 137200 | 165900 |
| Middle East | 124700 | 117100 | 129600 | 138600 | 145900 | 141000 | 140000 | 159400 | 167800 | 175400 | 191600 |
| Asia | 985100 | 1147100 | 1403200 | 1472900 | 1484400 | 1238100 | 1354500 | 1665500 | 1547900 | 1643000 | 1948400 |
| World total | 3874000 | 4426000 | 5279000 | 5535000 | 5725000 | 5664000 | 5902000 | 6705000 | 6466000 | 6714000 | 7778000 |
| **Exports** | | | | | | | | | | | |
| North America | 609990 | 678045 | 777005 | 826775 | 903180 | 896515 | 931285 | 1057815 | 990705 | 946315 | 996615 |
| Latin America | 161100 | 187400 | 228500 | 255600 | 284200 | 281300 | 300000 | 360600 | 348100 | 347500 | 377600 |
| European Union (15) | 1488885 | 1702895 | 2083745 | 2154900 | 2140890 | 2233600 | 2237460 | 2316290 | 2318780 | 2466250 | 2900735 |
| Africa | 93100 | 96800 | 111900 | 125100 | 127200 | 105200 | 116700 | 146900 | 137700 | 141100 | 173200 |
| Middle East | 125300 | 135900 | 150400 | 173400 | 180900 | 144500 | 186200 | 267200 | 246300 | 251800 | 298700 |
| Asia | 1064800 | 1228300 | 1447000 | 1464600 | 1543700 | 1448400 | 1546300 | 1833000 | 1672600 | 1805000 | 2110500 |
| World total | 3777000 | 4326000 | 5162000 | 5391000 | 5577000 | 5496000 | 5708000 | 6446000 | 6197000 | 6481000 | 7503000 |

* Source: www.wto.org

### 1.2.2. Risks in supply chain

The earthquake that struck Taiwan on September 21, 2000 knocked out production of some of the world’s top computer chip manufacturers. About a week later, the Associated Press (AP) reported that the quarterly profits of at least one Canadian high-tech firm will likely take a hit as a result of the tremor (McGillivary 2000). The 17-day strike in March 1996 at the Delphi brake plant in Dayton, OH shut down 26 of GM’s assembly plants and caused a nearly $1 billion hit to the company's first quarter earnings (Fitzgerald 1996). Two other strikes, at a stamping plant in Flint, MI and a nearby parts plant, in 1998 temporarily closed 25 of GM’s North American plants and affected nearly 90% of GM’s production capabilities. They also led to temporary shutdowns of plants owned by third-party suppliers. Hurricane Floyd hit nowhere close to southwestern Ontario. However, it shut down a Daimler Chrysler minivan plant in Windsor as well as six other plants across North America (McGillivary 2000). On March 17, 2000, a random lightning bolt caused a fire in a semiconductor plant in New Mexico. Although the fire only lasted about 10 minutes, it cost Ericsson $1.7 billion and changed the landscape of the global cellular telecommunications industry forever (Christopher and Peck 2004). When enjoying the benefits of focusing on their core competencies by outsourcing and adopting new business models such as Just-In-Time (JIT) manufacturing, e-procurement, and online auctions, firms also expose themselves to uncertain events, generally called “risks.”

To firms, risks in supply chains arise not only from their business partners such as suppliers, but also from customers, internal operations, new technologies, political issues, natural disasters, etc. Table 1.2 lists some risks that commonly exist in supply chains and their sources. Some risks can be reduced or even eliminated, but others are hard to control. How to successfully manage the risks in supply chains has become more and more critical to firms. Although a lot of firms have already realized the importance of supply chain risks, few are well prepared because of the complexity of the risk issues in supply chains and the lack of good techniques. A study completed by FM Global indicated that more than one-third of the financial executives and risk managers surveyed do not feel that they are adequately prepared for disruptions to their business. The 2003 Protecting Value showed 34% of respondents rated the extent of their preparation for disruptions to their major source of revenue as fair or poor (Bradford 2003).

**Table 1.2 Examples of risks and their sources in supply chains**

| Sources | | Risks |
|---|---|---|
| External | Suppliers | Failures to meet time/ quantity/quality requirements<br>Price fluctuations<br>Outmoded technologies |
| | Customers | Demand fluctuations in quantity and type for products or services<br>Order changes including quantity, type, and delivery time<br>Return |
| | Global business | Currency exchange rate fluctuations<br>Import tax rate change<br>Export restrictions<br>Reputation risk such as the anti-American wave in the Middle East |
| | Nature | Earth quake, flood, hurricane, blizzard, blackout |
| Internal | Human resources | Key employees leave<br>Short of employees for suddenly increased demands |
| | Technology | New technologies<br>Outmoded product design |
| | Management | Inappropriate business strategy |
| | Production | Failures to meet quality goals |
| | Finance | Failed investment<br>Stock price fluctuations |
| | Transportation | Failures to meet the time/quantity/quality promises to customers |

### 1.2.3. Suppliers

To respond to all the challenges coming from globalization, firms need to learn that their success now depends on how capable they are of promptly responding to customer requirements world-wide while keeping costs low. In other words, they have to focus on their core competencies to face decreasing product lives and increasing product variety requirements from customers. Radical changes have become necessary. Noticing that it becomes increasingly more difficult and less economical to produce the whole product on their own, outsourcing is becoming one of the main strategies for firms, and global outsourcing is more and more popular for cheaper labor and material costs as well as fast response to local demands.

One of the competencies essential to firms' success is an effective purchasing function (Giunipero and Brand 1996). Firms need to purchase raw materials, parts, components, and services from suppliers, and outsource part of or even the whole production to OEMs for lower costs and shorter product development cycles. The importance of purchasing and materials management continues to expand with the trend of global outsourcing. Firms are becoming more dependent on their suppliers for design and production. As this reliance grows, firms' performance increasingly depends on the actions of suppliers (Barbarosoglu and Yazgac 1997; Vonderembse and Tracey 1999). Figure 1.3 shows that a high percentage of the responding firms to a survey conducted by the Northeastern University and Accenture in 2004 use international 3PL services. Since business competitions is now among supply chains instead of individual firms, the challenge faced by firms is how to successfully manage their global supply chains, which are much more complicated, unpredictable, and uncontrollable compared to domestic supply chains.

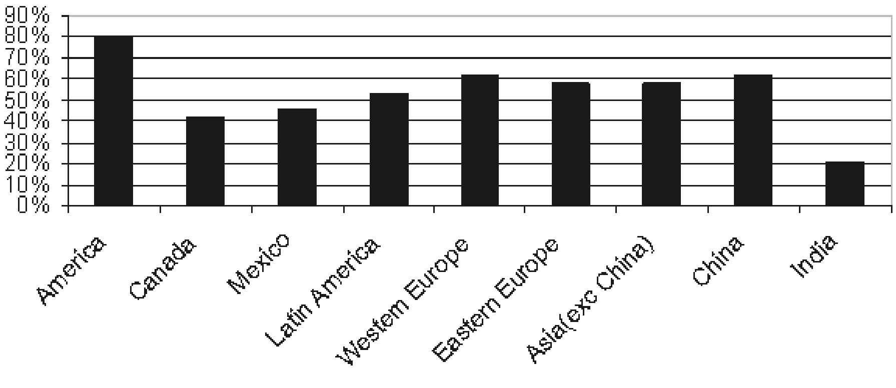


**Figure 1.3 The percentages of responding firms using international 3PL services**

The research done by Simpson et al. (2002) showed that less than half of the responding firms have a formal supplier evaluation process in place. It is quite natural to believe that even fewer of them have a formal evaluation process for global supplier selection and management considering business risks in which more factors need to be considered.

As one of the key factors for firms to achieve success, suppliers can bring significant risks to the whole supply chain. Everyday, 200 suppliers go bankrupt while a similar number open for business. Every hour, 360 suppliers will have a judgment filed against them, 112 have a change in senior leadership and 4 change their names. Suppliers must be assessed and focused on (Supplier Selection & Management Report 2003).

## 1.3. Research question

The unstoppable globalization trend makes global supply more and more common and thus supply chains become more and more complicated. At the same time, some business philosophies such as JIT put higher requirements on supply chains. Many real world events already show that supply interruptions can cause great revenue loss to firms. Therefore, how to manage supply risks has become a major question to which firms need to find an answer. The research question in this dissertation is defined as follows.

**How to manage supply risks quantitatively?** More specifically, this research plans to answer two questions:

1. How to quantify supply risks?
2. How to support decision-making regarding suppliers considering risks at both strategic and operational levels?

The primary research goal is to develop mathematical models to support a firm’s decision-making at both strategic and operational levels. The research tasks are:

- Develop mathematical models to quantify supply risks
- Develop several measures for supply risks

- Develop an optimization model considering risks to support decision-making at the operational level about order quantities, shipment options, production scheduling, etc
- Develop a mathematical model to support decision-making for supplier selection at the strategic level considering risks

## 1.4. Structure of the dissertation

Chapter 2 gives a comprehensive literature review in several related areas including supplier selection criteria and methods, global supplier selection and management, risks in supply chains, and risk management in supply chains. A new risk classification method is proposed in Chapter 3. Several related topics including the need for a risk monitoring system are discussed as well. A detailed research plan for each research task is given at the end of the chapter. Chapter 4 proposes a mathematical method to quantify supply risks. A flexible optimization model called "MTOM" is proposed in Chapter 5. It can optimize production, transportation, and inventory simultaneously considering risks at the operational level. It can also handle multiple products, transportation modes, manufacturing facilities, production lines, etc. The basic MTOM model was developed by the author as part of the Master's thesis. It is extended to handle supply risks in this dissertation. Chapter 6 proposes a 5-step supplier selection model at the strategic level considering risks. Chapter 7 summarizes the dissertation work and points out what further research can be done.

## 1.5. Expected contributions

The main contributions of this research will be:

1. A comprehensive risk classification method
2. A mathematical model to quantify supply risks
3. Several measures for supply risks
4. An optimization model that enables firms to make decisions at the operational level considering risks

5. A mathematical model that enables firms to select suppliers considering risks at the strategic level

# Chapter 2

# Literature Review

A literature review was performed in this section in the following areas, which were considered relevant to this research.

- Supplier selection criteria and methods
- Global supplier selection and management
- Risk in supply chains
- Risk management in supply chains

## 2.1. Supplier selection criteria and methods

The importance of supplier selection has been long recognized as the key responsibility of purchasing (England et al. 1975). Weber et al. (1991) pointed out that it is impossible to successfully produce low cost, high quality products without satisfactory vendors. Supplier selection has already become a strategic decision (Jayaraman et al. 1999). Recent studies have provided empirical evidence that supplier selection criteria, as well as supplier involvement, lead to improved buyer performance (Vonderembse and Tracey 1999). Supplier certification and regular assessment of supplier facilities are positively related to return on assets, growth in market share and sales, customer service, product quality, and competitive position (Tan et al. 1998). Suppliers are now deemed as “an increasingly important resource” (Handfield et al. 1999).

As one of the earliest and most cited literature source about supplier selection, a seminar paper by Dickson (1966) identified 23 criteria. Then, Weber et al. (1991) provided an explicit overview of supplier selection with special attention to the Just-In-Time (JIT) philosophy by reviewing 74 related papers. With the widespread concept of supply chain management (SCM), more and more scholars and practitioners have realized that competition is no longer company to company, but supply chain to supply chain (Vickery et al. 1999), and supplier selection and management is a vehicle to increase the competitiveness of the entire supply chain

(Lee et al. 2001). However, no comprehensive literature review has been published since 1991 except a working paper focused on supplier selection in *Supply Chain Management*. Forty-nine papers published from 1992 to 2003 were reviewed (Zhang et al. 2004).

Both the criteria used to evaluate suppliers and the methods used to choose the winners are extremely important for supplier selection. In the following sections, related literatures are reviewed.

### 2.1.1. Criteria used for supplier selection and evaluation

Table 2.1 summarizes the criteria reviewed by Dickson (1966), Weber et al. (1991), and Zhang et al. (2004).

**Table 2.1 Importance ranking of criteria for supplier selection**

| Criterion | Dickson (1966) | | Weber et al. (1991) | | Zhang et al. (2004) | |
|---|---|---|---|---|---|---|
| | Ranking | Rating[1] | Ranking[2] | % | Ranking[2] | % |
| Net price | 6 | A | 1 | 80% | 1 | 87% |
| Quality | 1 | A+ | 3 | 53% | 2 | 82% |
| Delivery | 2 | A | 2 | 58% | 3 | 73% |
| Production Facilities and Capacity | 5 | A | 4 | 30% | 4 | 44% |
| Technical Capacity | 7 | A | 6 | 20% | 5 | 33% |
| Financial Position | 8 | A | 9 | 9% | 6 | 29% |
| Geographical Location | 20 | B | 5 | 21% | 7 | 11% |
| Management and Organization | 13 | B | 7 | 13% | 7 | 11% |
| Performance History | 3 | A | 9 | 9% | 7 | 11% |
| Operating Controls | 14 | B | 13 | 4% | 7 | 11% |
| Communication Systems | 10 | B | 15 | 3% | 7 | 11% |
| Reputation and Position in Industry | 11 | B | 8 | 11% | 12 | 7% |
| Repair Service | 15 | B | 9 | 9% | 13 | 4% |
| Packaging Ability | 18 | B | 13 | 4% | 13 | 4% |
| Training Aids | 22 | B | 15 | 3% | 13 | 4% |
| Procedural Compliance | 9 | B | 15 | 3% | 13 | 4% |
| Labor Relations Record | 19 | B | 15 | 3% | 13 | 4% |
| Warranties & Claims Policies | 4 | A | - | 0 | 13 | 4% |
| Attitude | 16 | B | 12 | 8% | 19 | 2% |
| Reciprocal Arrangements | 23 | C | 15 | 3% | 19 | 2% |
| Impression | 17 | B | 15 | 3% | - | 0 |
| Desire for Business | 12 | B | 21 | 1% | - | 0 |
| Amount of Past Business | 21 | B | 21 | 1% | - | 0 |

Notes:

1. A+: Extremely important; A: Considerably important; B: Of averagely importance; C: Slightly important.
2. Ranking is based on the frequency of the criterion discussed in reviewed papers.

The following observations can be made from Table 2.1.

- Net price, quality, and delivery are always the most important and widely used criteria
- Warranties & Claims Policies ranks 4th in Dickson's study but not in later studies
- Financial position has become of greater concern since the 1990s
- Geographical Location has become of less concern since the 1990s
- Communication systems has become of greater concern since the 1990s

With shortened product life cycles, faster technology changes, global sourcing, and e-Business, existing criteria are extended. Table 2.2 lists some sub-criteria extended from two of the most important criteria: net price and delivery. Table 2.3 lists some new criteria for supplier selection in three categories.

The globalization of the business environment makes global supply more and more common even to middle- and small-size enterprises (MSEs). Thus more criteria need to be considered such as political stability, foreign exchange rates, tariffs, and customs duties (Min 1994; Motwani et al. 1999). Environment-related criteria have also been developed and involved in decision making (Zhu and Geng 2001; Humphreys et al. 2003).

### Table 2.2 Criteria extended from net price and delivery

| Origin | Extension | Literature source |
|---|---|---|
| Net Price | Fixed cost | Weber and Current (1993) |
| | Design cost and supplier cost | Gupta and Krishnan (1999) |
| | Inventory holding cost | Tempelmeier (2002) |
| | Fixed ordering cost | Tempelmeier (2002) |
| | Quality cost | Bhutta and Huq (2002) |
| | Technology cost | Bhutta and Huq (2002) |
| | After-sales service cost | Bhutta and Huq (2002) |
| | Total cost of ownership | Bhutta and Huq (2002) |
| Delivery | ISO 9001 | Bello (2003) |
| | Inspection, experimentation and quality staff | Choy and Lee (2002) |
| | Freight terms | Min (1994) |
| | Lead time | Youseef et al. (1996) |
| | Delivery capacity | Karpak et al. (1999) |
| | Shipment quality | Choy and Lee (2002) |
| | Cycle time | Bevilacqua and Petroni (2002) |
| | JIT delivery capacity | Bevilacqua and Petroni (2002) |

### Table 2.3 Examples of new criteria for supplier selection

| Category | Criterion | Literature source |
|---|---|---|
| Product design & Improvement | Design capability | Pearson and Ellram (1995)<br>Chan (2003) |
| | Product development and product improvement | Choy and Lee (2002) |
| | Commitment to continuous improvement in product and process | Kannan and Tan (2003) |
| Flexibility and responsiveness | Responsiveness to customer needs | Mummalaneni et al. (1996) |
| | Response to changes and process flexibility | Ghodsypour and O’Brien (2001) |
| | Flexibility in changing orders | Verma and Pullman (1998) |
| | Flexibility of response to customers requirements | Bevilacqua and Petroni (2002) |
| | Quote flexibility | Kumar et al. (2004) |
| | Ability to respond to unexpected demands | Kannan and Tan (2003) |
| Collaboration | Level of assistance in mutual problem solving | Gunasekaran et al. (2001) |
| | Willingness to integrate supply chain | Kannan and Tan (2003) |
| | Willingness to share confidential information | Kannan and Tan (2003) |

### 2.1.2. Current supplier selection approaches and models

Thompson (1990) pointed out that most published models and methods had fallen into three categories: categorical methods, weighted point methods, and cost-based techniques including cost-ratio. Weber et al. (1991) categorized supplier selection approaches into three categories: linear weighting models, mathematical programming models, and statistical/probabilistic approaches. After his research, more methods began to emerge such as Vendor Profile Analysis. Zhang et al. (2004) showed that in the 49 articles they reviewed, 13 articles were either empirical or conceptual studies, 8 articles used linear weighting methods (22% of 36), 15 articles used mathematical programming models (42% of 36), and the remaining 10 (28% of 36) used other methods. In the following section, these methods are grouped into four categories and reviewed.

#### 2.1.2.1. Linear weighting models

In these models, basically potential suppliers are rated on several criteria and the ratings are then combined into a single score to choose the "winner". Among these models, the most popular are the categorical, the weighted point (Timmerman 1986), and the Analytical Hierarchical Process (AHP) (Nydick and Hill 1992).

**Categorical models**

Categorical models are the first among traditional models for supplier evaluation. According to these models, suppliers are evaluated on criteria such as cost, quality, speed of delivery, etc (Youssef *et al.* 1996). A rating is given in each of the selected performance categories, and an overall group evaluation is then given.

The primary advantage of the categorical approach is that it helps structure the evaluation process in a clear and systematic way. By requiring buyers to explicitly consider the evaluation criteria used in their decisions, they are compelled to determine which supplier attributes they should truly value.

An obvious disadvantage of this technique is that it typically does not clearly define the relative importance of each criterion. These models tend to be fairly subjective (Nydick and Hill 1992), and rely heavily on the experience and abilities of the individual buyers (Timmerman 1986). People in charge of purchasing, quality, production, service, and sales all express their individual opinions about the performance of suppliers based on what criteria are important to them without enterprise-wide consideration.

### Weighted point approach

Weight is assigned to each attribute of potential suppliers that is important. Then, the performance score for each attribute is multiplied by the assigned weight for each supplier, and these weighted scores are totaled to determine the final rating for each supplier (Timmerman 1986).

The weighted point approach overcomes the major disadvantages of the categorical approach. All measurement factors are weighted according to their importance in each purchasing situation. It enables purchasing firms to take as many attributes into consideration as they need, and the subjective factors on evaluation are reduced.

Typically, the weighted point approach requires quantitative measurements. Therefore, the major disadvantage is that it is difficult to effectively take qualitative evaluation criteria into consideration (Nydick and Hill 1992).

### Vendor Profile Analysis (VPA) model

VPA extends the weighted point methodology by simulating the performance rating for each criterion. It captures the uncertainty that may exist in reality by using the Monte Carlo simulation technique, and it is a substantial improvement over the single point estimates used in the weighted point method. The evaluation process involves a series of one-on-one comparisons (Thompson 1990). It can be expanded to most linear applications and cost-based evaluation models as well as the cost-ratio method. The implementation is also simple. It can be adapted to virtually any type of purchase decision (Robinson and Timmerman 1987). However, it still does not adequately measure qualitative evaluation criteria (Nydick and Hill 1992).

### Matrix models

In matrix models, suppliers are evaluated on weighted factors such as proposal responsiveness, technical merits, quality, cost and general factors (Gregory 1986). Each factor is divided into a group of sub-factors and suppliers are then ranked based on weighted scores. The supplier with the highest overall score will be selected. The application is simple but subjectivity is still a significant problem.

### Analytical Hierarchy Process (AHP)

The supplier selection process addresses different functions within the business organization. It is inherently a multi-objective decision-making problem, encompassing many tangible and intangible factors in a hierarchical manner.

Developed by Satty (1980), AHP is a decision-making method for ranking alternatives when multiple criteria must be considered. It allows the decision maker to structure complex problems in the form of a hierarchy, or a set of integrated levels.

Narasimhan (1983) first suggested using AHP for supplier selection in order to overcome any of the shortcomings of the previous procedures. Zhang et al.'s (2004) study shows that AHP is the most commonly used method in linear weighting models. Nydick and Hill (1992) summarized the application of AHP in the supplier selection process into the following five steps:

step 1. Specify the set of criteria for evaluating the supplier's proposals.

step 2. Obtain the pair-wise comparisons of the relative importance of the criteria in achieving the goal, and compute the priorities or weights of the criteria based on this information.

step 3. Obtain measures that describe the extent to which each supplier achieves the criteria.

step 4. Using the information in step 3, obtain the pair-wise comparisons of the relative importance of the suppliers with respect to each of the criteria, and compute the corresponding priorities.

step 5. Use the results of steps 2 and 4 to compute the priorities of each supplier in achieving the goal of the hierarchy.

They also summarized the following advantages of using AHP in supplier selection.

- It is a flexible modeling tool that can accommodate a larger set of evaluation criteria.
- It supports a group decision-making process.
- It is simple.
- It can accommodate uncertain and subjective information, and allows the application of experience, insight, and intuition in a logical manner.
- It forces buyers to seriously consider and justify the relevance of the criteria.

However, a major disadvantage of AHP is that the method becomes very cumbersome when there are a lot of criteria and suppliers because too many pair-wise comparisons have to done.

There are several papers that introduce the application of AHP such as Barbarosoglu and Yazgac (1997) who showed how to use the AHP model to solve the supplier selection problem in Turkish industry.

#### 2.1.2.2. Cost-based approaches

**Cost ratio**

Cost ratio is a method that relates all identifiable purchasing costs to the monetary value of the goods received from vendors (Timmerman 1986). For example, quality cost includes the cost of visits to a vendor’s plants and sample approval, inspection costs of incoming shipments, and the costs associated with defective products such as unusual inspection procedures, rejected parts and manufacturing losses due to defective goods. Delivery cost includes communications, settlements and emergency transport costs such as air shipments. The higher the ratio of costs to value, the lower the rating applied to the vendor. The choices of costs to be incorporated in the evaluation depend on the products involved.

The advantage of this method is its flexibility. Any company in any market can adopt it. The drawbacks are the complexity and the requirement for a developed cost accounting system to generate the precise cost data needed (Timmerman 1986).

**Total cost of ownership**

The total cost of ownership method attempts to quantify all of the costs related to the purchase of a given quantity of products or services from a given supplier (Degraeve and Roodhooft 1999). Besides the net price, other cost factors are also considered including the costs associated with quality shortcomings, a supplier's unreliable delivery service, transport costs, ordering costs, reception costs, and inspection costs. This method uses an activity-based costing technique which assigns costs to cost-generating activities within a business. The first step is to define all the activities related to external purchasing, and assign costs to those different activities. The next step is to define factors which raise the cost of a given activity. Finally, activities generated in the purchasing organization by each individual supplier are identified. The advantages of this approach are that it makes substantial cost savings achievable, and it allows various purchasing policies to be compared at the same time.

#### 2.1.2.3. Mathematical models

As early as in 1973, it was recognized that optimization models can be used for selecting suppliers.

> "These models (linear programming) would have as their objective the analysis of any combinations of multi-price, multi-supplier, multi-item, multi-user, multi-time period procurement situations... The computer program would manipulate the data to arrive at an optimum mix of supplier awards under the given constraints. These constraints may take the form of a limitation placed on the amount of business any supplier could be awarded... Program options might include an ability to measure the outcome and economic effect of altering the constraints... Such models are almost a necessity for the comprehensive analysis of large contracts involving many items and many suppliers." (Moore and Fearon 1973)

Since then, mathematical models have become more and more important in supplier selection. Although only 14% of the reviewed papers in Weber et al.'s (1991) study employed mathematical programming models to solve supplier selection problems, this number increased to 42% in Zhang et al.'s (2004) study. The most popular ones are:

- Linear programming
- Non-linear programming
- Mixed integer programming
- Goal programming
- Multiple-objective programming
- Data Envelop Analysis (DEA)

The reason for the popularity of mathematical programming models is that they can solve some problems that traditional supplier selection methods cannot handle such as supplier combination as well as associated order quantities. The main drawback is that they are limited to quantitative criteria and most of them are too complex for practical use. Table 2.4 shows some of the mathematical programming models used in recent research papers.

**Table 2.4 Mathematical programming supplier selection models in recent research papers**

| Paper | Linear | Non-linear | Mixed integer | Goal | Multi-objective | Objectives and comments |
|---|---|---|---|---|---|---|
| Weber and Current (1993) | | | ✓ | | ✓ | Minimize total purchasing cost, late delivery, and rejected units |
| Weber and Ellram (1993) | ✓ | | ✓ | | ✓ | Minimize total purchasing cost, late delivery, and rejected units while allowing a varying number of suppliers into the solution and provide suggested volume allocations among suppliers |
| Chaudhry et al. (1993) | ✓ | | ✓ (Binary) | | | Minimize cost with price breaks |
| Rosenthal et al. (1995) | ✓ | | ✓ | | | Minimize total purchasing cost |
| Ghodsypour and O'Brien (2001) | | ✓ | ✓ | | | Minimize total cost in multiple sourcing condition |
| Tempelmeier (2002) | ✓ | | ✓ | | | Minimize cost under dynamic demands condition |
| Dahel (2003) | | | ✓ | | ✓ | Determine multiple suppliers and order quantities in multiple-product and multiple-supplier environment driven by price, delivery, and quality objectives |

#### 2.1.2.4. Statistical approaches

**Principal Component Analysis (PCA)**

The PCA method is a multi-objective approach for vendor selection which attempts to provide a useful decision support system for a purchasing manager facing multiple vendors and trade-offs such as price, delivery, reliability, and product quality (Petroni and Braglia 2000). It is a data reduction technique used to identify a small set of variables that account for a large portion of the total original variance. This technique is also used to identify “latent” dimensions in the data. In fact, the principal component analysis computes linear combinations of variables.

PCA can simultaneously consider multiple inputs and multiple outputs without any need for an assignment of weights. It is also not necessary to state the performance measures in the same units. The relevant attributes of suppliers can be measured in any unit such as money, percentages, or qualitative subjective judgments. Furthermore, PCA is less subjective than some traditional methods because it doesn’t force decision makers to do standardized ratings for attributes. It is also fairly simple to exploit.

#### 2.1.2.5. Other approaches and models

Besides the above-described mainstream supplier selection approaches and models, there are also many other methods, some of which combine certain methods from the different categories above. Table 2.5 lists some of those found in the literature.

There are also other papers specially focusing on certain characters of suppliers, certain types of suppliers, or suppliers in certain areas. Shore and Venkatachalam (2003) used Fuzzy Logic, a subset of artificial intelligence together with AHP to evaluate the information-sharing capabilities of supply chain partners and to rank potential suppliers. Garrett (2003) gave a summarization of how to assess an unknown supplier.

**Table 2.5 Other supplier selection approaches and models**

| Paper | Methods, models, and comments |
|---|---|
| Hinkle et al. (1969) | Using cluster analysis |
| Parasuraman (1978) | A sequential elimination procedure |
| Gregory (1986) | Using an internal sourcing worksheet based on the weighted factor matrix approach |
| Bevilacqua and Petroni (2002) | Fuzzy logic approach |
| Ghodsypour and O'Brien (2001) | Integration of AHP and linear programming |
| Karpak et al. (1999) | Visual interactive goal programming |
| Wei et al. (1997) | Neural network |
| Mandal and Deshmukh (1994) | Interpretive structural modeling |
| Min (1994) | Multiple-attribute utility approach |
| Kwong et al. (2002) | Combination of fuzzy expert system with scoring method |

### 2.1.2.6. Comparison

Table 2.6 compares some of the above methods and approaches highlighting the advantages and disadvantages of each.

**Table 2.6 Comparison of some popular supplier selection methods**

| **Method** | **Reference** | **Quantitative/Qualitative Parameters** | **Advantages** | **Disadvantages** |
|---|---|---|---|---|
| Categorical | Timmerman (1986) | -Quality<br>-Delivery<br>-Service<br>-Price | -Clear and systematic evaluation process<br>-Low cost<br>-Low performance data requirement<br>-Compelling users to determine which supplier attributes they truly value | -Missing the relative importance of each criterion<br>-Subjective<br>-Inaccuracy |
| Weighted point | Timmerman (1986) | -Quality<br>-Delivery<br>-Service<br>-Price | -Attributes are weighted by importance | -Subjective<br>-Difficulties in effectively considering qualitative criteria |
| Vendor Profile Analysis (VPA) | | | -Be able to capture the uncertainty over single point estimate | -Inability to handle qualitative criteria |
| Cost ratio | Timmerman (1986) | -Quality<br>-Delivery<br>-Service<br>-Price | -Reduced subjectivity<br>-Flexibility | -Complexity<br>-Requirement of a costly developed cost accounting system<br>- Requirement of expressing performance measures in same units |
| Total cost of ownership | Ellram (1995) | -Price<br>-Quality costs<br>-Unreliable delivery service costs<br>-Transport costs<br>-Ordering costs<br>-Reception costs<br>-Inspection costs | -Substantial cost savings<br>-Supporting the comparison of various purchasing policies. | -Complexity |
| Principal Component Analysis (PCA) | Petroni & Braglia (2000) | -Price<br>-Delivery reliability<br>-Quality | -Considering multiple inputs and outputs simultaneously without requiring weight assignments | -Requirement of skills in statistics |

| | | | | |
|---|---|---|---|---|
| Analytic Hierarchy Process (AHP) | Nydick & Hill (1992) | -Quality<br>-Price<br>-Delivery<br>-Service | -Simplicity<br>-Accepting both qualitative and quantitative criteria<br>-Supporting multiple-objective decision making<br>-Virtually no limits on the number of evaluation criteria<br>-Supporting group decision making | -Inconsistency<br>- Inability to solve problems with multiple criteria and suppliers |
| Neural Network | Wei et al. (1997) | -Performance<br>-Quality<br>-Geography<br>-Price | -Time and money savings in system development | -Expertise requirement<br>-Software requirement |

Main references: Bello 2003; Nydick and Hill 1992

## 2.2. Global supplier selection and management

The definition of world-class manufacturing requires that a firm not only competes globally in the marketplace, but also becomes competitive in cost, leads in technology, and is consistent in quality. This requires that firms do not limit their playing-field to their own country, but see customers, partners, and suppliers in other countries as well (Spekman 1991). However, compared to domestic supplier selection and management, global suppliers are much more difficult to deal with due to the following reasons.

- **More obstacles**

  Different countries have different regulations about import and export, different industrial standards, different cultures, different ways of doing business, and even different languages. In order to work closely with international suppliers, firms need to adapt to those differences. The adaptation process usually is not easy and in many cases, firms have to learn costly and painful lessons when they are trying to overcome those obstacles.

- **Lack of accurate information**

  Information is the basis for decision making. Getting accurate and comprehensive information about suppliers in foreign countries is usually difficult especially when trying to find long-term and/or critical suppliers. Min and Galle (1991) found that many firms would turn to professional contacts, trade journals, directories, trading companies, import brokers, and other outside sources to obtain information about foreign suppliers. Industry or national certifications such as ISO 9001 sometimes are the main factor for the final decision. However, more information is needed to make the right decisions, especially when firms are trying to build a long-term relationship with those potential suppliers. For example, their R&D capabilities, the compatibilities of business strategies as well as information systems, the abilities of handling risks, and the efforts for continuous improvement are also critical.

- **Higher risk**

  Risks associated with international suppliers usually are higher than risks from domestic suppliers, and there are more risks such as currency exchange fluctuations, shipment delays, political issues which can shutdown border, etc. Regulations from foreign governments such as packaging requirements and government inspections also cause risks because of the extra cost and potential delay.

So far, not much research has been done specifically for global supplier selection. One of the possible reasons is the lack of reorganization of the differences between domestic supplier selection and global supplier selection. Few of the existing papers focus mainly on selection criteria. Katsikeas and Leonidou (1996) reported a systematic investigation of international selection criteria of UK distributor firms trading with US exporting manufacturers of industrial products. They attempted to explore the existence of dimensions underlying overseas supplier selection criteria and identify potential differences in perceptions of such choice criteria based upon the degree of import dependence. Their findings pointed out certain product offers and supplier characteristic elements in influencing import decision-making pertaining to foreign supplier selection.

## 2.3. Risks in supply chain

In today’s highly competitive business environment, product lives keep decreasing while customers require more variety and quicker delivery. In order to survive, firms have to focus on their core competencies. They need to purchase raw materials, parts, components, and even services from suppliers, and outsource part of or even the whole production to OEMs for lower costs and faster product development cycles. They need to adopt business models such as e-procurement and online auctions to catch the trends and broaden their markets. While enjoying all the benefits of the above, firms also expose themselves to uncertain events, which are generally called “risks.”

Zsidisin (2003) defined supply risk as “the potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market, in which its outcomes result in the inability of the chasing firm to meet customer demand or cause threats to customer life and safety.” An example in the supply chain context is the flood caused by Hurricane Floyd in North Carolina that shut down a Daimler Chrysler plant in Greenville, and thus caused a shortage of suspension parts. As a result, seven other Daimler Chrysler’s plants across North America were shut down. Another example is the earthquake in Taiwan on September 21, 2000, which affected the quarterly profits of the high-tech companies in Canada (McGillivary 2000).

There is a significant literature in management and operation research that discusses risks (Ruefli et al. 1999). However, limited research has been done on risk assessment, contingency plans, and risk management within the context of in-bound supply (Zsidisin et al. 2000). After Y2K, September 11, the West Coast dock workers’ strike in 2002, SARs, etc, more and more attention has been drawn to the risk issues in supply chains (Souter 2000; Zolkos 2003).

Because of the complexity of supply chains, numerous risks exist in them. In today’s highly integrated supply chains, any breakdown of a small part could affect the whole chain and cause tremendous loss. In order to control the risks in supply chains, risks and their resources need to be identified at the outset. Table 1.2 listed some examples of the risks commonly occurring in supply chains and their sources.

There are different ways to categorize risks in supply chains. Johnson (2001) suggested that when viewed as a whole, in the toy industry, risks fall into two major categories: supply risks (including capacity limitations, currency fluctuations, and supply disruptions) and demand risks (including seasonal imbalances, volatility of demands, and new products). Table 1.2 divides the risks in a supply chain into two categories: external and internal. Generally, external risks are from outside and includes business partners, natural environment, government, and competitors. Internal risks are from inside and include business and production operations, management strategies and activities, and employees. Basically, firms have better control over internal risks than external risks.

Due to the complexities and varieties of the risks in supply chains and the limited resources that companies have, it is impossible to eliminate all the risks. Therefore, some authors believed that only the key risks and their sources should be identified and focused on. Zsidisin et al. (2000) identified six key risks: business risks, supplier capacity constraints, quality, production technological changes, product design changes, and disasters. Zsidisin and Ellram (2003) identified five sources of supply risks: unanticipated changes in the volume requirements and mix of items needed, production or technological changes, price increase, product unavailability, and product quality problems.

### 2.4. Risk management in the supply chain

A study completed by FM Global indicated that more than one-third of the surveyed financial executives and risk managers did not feel that their firms are adequately prepared for disruptions to their business. The 2003 Protecting Value showed 34% of respondents rated the extent of their preparation for disruptions to their major source of revenue as fair or poor (Bradford 2003).

In order to reduce the risks in the supply chain, some general procedures and rules were suggested. Anonymous (2003) suggested a 5-step plan to minimize supplier and inventory risk across supply chains:

1. Define the critical materials and services
2. Identify critical materials and service and their suppliers
3. Perform a risk assessment of the identified suppliers
4. Develop contingency plans
5. Put the contingency plans in place

Atkins (2003) listed 10 tips to secure a supply chain:

1. Be proactive; Know the vulnerabilities
2. Know your business partners; Make unannounced visits to them
3. The human elements. Train the employees and retrain them continuously

4. Share information with your partners
5. Join security programs
6. Maintaining precise inventory control
7. Plan for business continuously; Once the vulnerabilities are determined, mitigation and contingency plans need to be developed to address the most critical and most likely vulnerabilities
8. Automate information flow
9. Re-evaluate constantly
10. Ensure the physical security of your products and shipments

Some papers introduced ways to handle risks in certain industries: Johnson (2001), for example, discussed risk management in the toy industry. Based on the space shuttle orbiter's supply chain, McClain (2000) introduced the implementation of a comprehensive risk management program that ranks logistics risks.

### 2.4.1. Current solutions adopted by firms

#### Multiple suppliers

Although single sourcing offers some excellent opportunities to achieve economies of scale and control of purchase to firms (Youssef et al. 1996), it is very dangerous to depend on a single source (Newman 1990). The most common method strategically employed by firms to control and reduce supply risks is multiple supply sources. The advantage is obvious. When one supplier fails, a firm can still get supplies from the others although the cost might be higher in most cases. HP is a successful example of using this method. HP's procurement groups use the "portfolio" strategy, usually used by financial investors, to diversify and spread the supply risks over a number of suppliers. Under the portfolio model, HP enters into a structured contract with suppliers. Anticipating future component pricing trends and evaluating what its longer-term requirements will be, HP agrees to buy a set amount over a period of time. The OEM assumes the risk for that volume, regardless of changes in market conditions or fluctuations in supply or demand. In return, suppliers will likely provide better pricing, aware that HP's commitment will be over an extended period, and will be able to plan resources accordingly. Basically, HP takes the risk and gets paid from suppliers for taking the risk (Shah 2001). HP also uses the same method to broaden its labor alternatives. By using a mix of full time employees, part-time contractors, consultants, and temps, HP increases its flexibility to match labor supply with fluctuating demand and reduces labor costs by 13% (Billington 2002).

### Contingency plans

Several papers have drawn attention to the fact that firms need contingency plans to handle sudden interruptions in today's highly efficient and integrated supply chains (Aldred 2003). A company should first consider the range of likely risks and their possible impacts on operations, and then set priorities to focus on the major risks (Zolkos 2003). To identify exposure, the company must identify not only direct risks to its operations but also the potential causes of those risks at every significant link along the supply chain (Gilbert and Gips 2000). Then the company can work on "actionable" risks. The final step is integrating that information into the organization's contingency plans so that when an event does occur, the company can respond appropriately (Zolkos 2003).

### Join professional programs

A wise choice for companies to ensure that they are up-to-date on risk management in their supply chain is to become a certified member of various programs that have been implemented since September 2001 such as C-TPAT and CSI. "The Customers-Trade Partnership Against Terrorism" (C-TPAT) program asks companies to take concrete steps to secure their global supply chains at every stage from manufacturing plants to ultimate destinations. "The Container Security Initiative" (CSI) program places US customs officers in many foreign ports to work with local customs authorities to examine "high-risk" containers before they are loaded onto a vessel. In Canada, there are the "Customs' Self Assessment" (CSA) program and “the Free And Secure Trade” (FAST) program, which are designed to ensure speedier border crossings by pre-certifying carriers and shippers as low risk (Atkins 2003).

Table 2.7 shows some the best practices of risk management in supply chain which have been identified so far at both the strategic and operational levels.

**Table 2.7 Best risk management practices in supply chain from industry**

| | |
|---|---|
| **Strategic Level** | • Monitoring current or potential business partners’ performance<br>• Requiring key business partners to have risk management plans<br>• Considering risks when choosing business partners<br>• Improving collaboration<br>• Improving visibility in supply chain<br>• Using “portfolio” strategy<br>• Joining professional programs such as C-TPAT,CSI, CSA, and FAST<br>• Buying insurance<br>• Reviewing current business models<br>• Special funding and cash reserve |
| **Operational Level** | • Keeping scheduled meetings with key business partners for risk issues<br>• Learning the lessons<br>• Preparing contingency plans<br>• Forming special teams to handle risks from different divisions and business partners<br>• Considering and controlling risks in all related business operations including product design, promotions, etc<br>• Getting regular employees involved and conducting training programs |

Main Source: Elkins et al. (2005)

### 2.4.2. Important topics about risk management in a supply chain

In this section, several important topics that need to be considered for risk management in a supply chain are discussed.

#### Business models

Current business models such as Vendor-Managed Inventory (VMI) should be reevaluated considering risks. Suppliers are placing tougher restrictions on their supply chain partners now such as limiting cancellation and return privileges and pressuring OEM customers to accept some degree of liability for the inventory that is ordered but never used. They have developed very specific contracts that define the exact time point from which the OEMs become liable for the inventory. They are also asking OEMs to benchmark their processes so that all participants in the VMI program can review the process (Sullivan 2003).

JIT (just-in-time), which is widely seen as a revolutionary new business process approach that has produced significant cost-efficiency savings, should also be reconsidered. Essentially, under JIT, a minor disruption in the supply chain can grind manufacturing to an expensive halt (McGillivary 2000). JIT also has other types of side-effects. Toyota’s Indiana-based manufacturer of forklifts receives parts deliveries by trucks five times a day. This is a common transportation mode for a JIT-based manufacturer. Consequently, the method has been accused of putting more heavy trucks on the road. It has also been blamed for pressuring truckers to drive harder, longer and faster because the customer must have the delivery in order to prevent a costly shutdown. According to opponents, this has led to an increase in major road accidents (McGillivary 2000).

### Supply chain design

When designing a supply chain, besides cost and flexibility, risk should also be considered as a major decision factor. Multiple production sites are safer than single site since the possibility of all of them having production disruptions at the same time is much lower. However, high-tech manufacturers probably do not want to do this due to the heavy investment required by production lines. Therefore, final decisions are always based on trade-offs.

The selection of transportation modes and routes is important as well. A survey polled more than 600 companies in 8 European countries after the September 11 tragedy. It showed that nearly a fifth of companies in the retail sector, which are more flexible in their freight demands, have considered a move away from air transport.

However, those companies in the high-tech manufacturing sector said that switching to other forms of freight was unfeasible because of the time-critical nature of their supply demands (Parker 2002).

### Supplier selection

So far, the research that has been done on supplier selection has mainly focused on cost, quality, and flexibility. Risk issues have seldom been considered comprehensively. In order to have a "safe" supply chain, a firm needs to evaluate the risks associated with its current and potential suppliers. An evaluation process should to be established to find out which suppliers can bear risks best in given situations.

When Johnson & Johnson tried to identify its critical suppliers, a special team was formed and it conducted a supplier process vitality check covering six categories: operations related aspects (including capacity, stability, and emergency preparedness), quality, financial vitality, engineering/technical expertise including IT, dependability and conformance to delivery schedules, and strategy and leadership (Atkinson 2003). Table 2.8 lists some of the risk-related information that firms need to collect when selecting and evaluating suppliers.

**Table 2.8 Checklist for suppliers**

| Categories | Examples of required information |
|---|---|
| Capacity constraints | Regular production capacity |
| | Overtime production capacity |
| | Delivery capacity |
| Cost | Cost reduction capabilities |
| Quality | Average defective rate |
| | Maximal defective rate |
| | Consistency |
| Business mode | Long-term strategy |
| Human resources | Employee satisfaction rate |
| | Stability of employees especially those in key positions |
| Technology | Information system compatibility |
| | New product development capability |
| Finance | Credit rating |
| | Company type |
| | Debt & loan rate |

Firms should understand that their success partially depends on the success of their suppliers. Unfortunately, the practice has been unsatisfactory in the real world. For example, when the world was dealing with Y2K problems, even though some giant auto companies such as GM, Ford, and DaimlerChrysler did try to help their suppliers through the Automotive Industry Action Group (AIAG), small suppliers still did not get enough help. Their failures could have posed big risks to the supply chains they joined (Melymuka 1999).

As discussed above, a multiple supplier strategy makes firms safer. However, it is not perfect. Firms can not always get the lowest price, and the more suppliers a company has, the more complicated the supply chain will be. In order to lower the management complexities, some companies adopt different strategies. Weyerhaeuser Co. in Federal Way, Washington, has narrowed the number of its suppliers down to a few, and has put a lot of pressure on them to do the job. With only a few suppliers, administration tasks are simpler and it is easier to ensure the quality of goods those vendors provide (Bradford 2003). Also in some special cases, multiple supply sources can not be attained. The only choice to companies is to help the existing supplier develop the needed competency (Zsidisin et al. 2000).

### Outsourcing

Outsourcing is a major strategic solution firms adopt to improve their competitive advantage. However, little research has been done on the associated risks although the current situation is not optimistic. Most of the research undertaken on outsourcing has revealed that a majority of managers are dissatisfied with the outcome of their decisions. Firms lack the awareness of how they can become dependent on other companies, and the danger of dependency (Lonsdale 1999). Therefore, how to manage the risks of outsourcing should be carefully considered by firms, especially those that have a large percentage of production outsourced.

### Risk monitoring

The best way to deal with risks is to prevent them from happening. When they are unavoidable, the earlier firms detect them, the smaller the impact will be. Firms need risk monitoring systems to cover the whole supply chain, including suppliers, OEMs, retailers, 3PLs, etc. Those supply chain members that firms do not directly deal with should still be monitored if possible. For example, company A is a raw material supplier for component manufacturer B, and B is a component supplier for company C. C should monitor A if A is a critical supplier to B and B is a critical supplier to C. This is because even though C does not directly deal with A, if for some reason, A cannot make its time/quantity/quality promises to B, C is very likely going to have some supply problems from B sooner or later.

Appropriate monitoring strategies should be developed. It does not make any economic sense to monitor all the risks in real time. Some methods from other areas can be applied here such as the ABC method and the Pareto 80/20 rule. Depending on the type of risk and the severity of corresponding effects, some should be monitored in real time and some should be monitored periodically. For the others, an event-triggered monitoring process could be used. For example, natural disasters such as flood can cause supply disruptions. However, firms do not need to monitor the weather in real time, but they can begin to focus on it after certain events happened, such as heavy rains.

## 2.5. Global supply risk management

Risk management is a relatively new topic in SCM, and so far, no research papers have been found specifically about global supply risk management. Compared to domestic supply chains, more risks exist in global supply chains and the situation is more complicated. Therefore, risk management for global supply is more difficult. As more and more firms adopt global supply as one of their major business strategies, both researchers and decision makers from industries should pay increases attention to this topic.

# Chapter 3

# Supply Risk Management

With the globalization trend, today's businesses become increasingly integrated and complicated, especially for manufacturing industries. As an inherent part of business, more risks are generated from firms' global operations. Although different firms may have totally different business strategies, markets, products, etc., all of them need to manage the risks in their supply chains successfully. This is a live-or-die situation in today's highly competitive business environment. As discussed in Chapters 1 and 2, due to the increasing importance of suppliers in supply chains, this research will focus on supply risk management. The general ideas and the models which will be developed in later chapters can be used for both domestic and global suppliers.

Although risk management has already been conducted in some areas such as banking, insurance, and financial industries, it is a relatively new topic in supply chain management. Since its appearance, it has drawn a lot of attention from both firms and researchers, especially after the September 11 tragedy. Generally, there are two basic steps for risk management in supply chain:

Step 1. Risk mapping including risk identification, risk analysis, risk classification, and risk prioritizing

Step 2. Risk mitigation and contingency planning

## 3.1. Risk mapping

Risk mapping was originally a tool used by life insurers in the identification, control, and management of risks. Figure 3.1 shows the basic risk mapping cycle. In the following part of this section, firms' need for a supply risk monitoring system is discussed and a new risk classification method is proposed.

**Figure 3.1 Basic risk mapping cycle**

### 3.1.1. The need for a risk monitoring system

Risk identification is the very first step for any risk management process. Although there are several papers discussing how to identify risks in supply chains, they are very general and not supply-focused.

As discussed in Chapters 1 and 2, risks arise from many sources including various business operations, business partners, environment, etc., and they keep changing all the time. Some existing risks might disappear after certain changes occur inside and/or outside the supply chain, while new risks can show up anytime. Therefore, risk identification is not a one-time job. Firms should continuously check for new risks while paying attention to those identified previously. A risk monitoring system should be built to help firms to conduct these activities systematically, efficiently, and promptly. A supply risk monitoring system should have the following two main functions:

1. Monitoring risk events that can affect the supply chain
2. Monitoring suppliers’ performance

### Monitoring risk events inside and outside the supply chain

Obviously, firms need to know what happens inside their supply chains, but what happens outside the supply chains that could affect the smooth flow of material and cause supply disruptions should also be monitored. For example, manufacturer A in

Pennsylvania has a supplier B in China: ordered parts from B are delivered to Los Angeles by ship at the beginning of every month, and then shipped to A by truck. Suppose the dock workers decide to go on strike in California since their requirements for a salary increase are not satisfied by employers. Then, without preparation, A can run out of supply for weeks and the production lines may have to be totally shut down. But if A has a good supply risk monitoring system, and it can notify A's decision makers that the ongoing negotiation between harbor workers and their employers was not going well several weeks ago according to news reports and the supply from B will be affected, A could then use some contingency plans to reduce the possible negative impacts. Compared to a strike in Los Angeles harbor, a flood in China close to B's manufacturing facility has much less chance of drawing A's attention, although the result could be the same.

### Monitoring suppliers' performance

This includes both current suppliers and potential suppliers, which are also important for supply risk management. In supply chains, firms primarily need to do the following two things regarding their current suppliers:

- Collaborate with them to improve their performance
- Monitor their performance and make necessary decisions promptly, such as replacing certain suppliers with more effective ones

In either case, firms need information about potential suppliers to support their decisions. At first, the information can be used to benchmark current suppliers. Thus firms can know which aspects current suppliers need to improve and how much improvement they should be able to achieve. Secondly, if certain current suppliers can not maintain their overall advantage vis-à-vis their competitors, firms can replace them with better suppliers. Thirdly, the information can help firms to mitigate risks. When certain current suppliers suddenly fail, with the necessary information in hand, firms can promptly find the best alternate supply sources to minimize the negative impacts of supply disruptions. The case of Nokia and Ericsson, which will be introduced in detail later, is a good example. If Nokia had not had information about alternate suppliers in Japan and in the United States, it would not have been able to get emergency supplies promptly from them to greatly reduce the loss. Always having backup suppliers ready is a good strategy to mitigate supply risks.

Another advantage of monitoring potential suppliers is that the information can help firms make the right decisions promptly for some other business operations such as product design. When firms design a new product, in most cases they need to consider the availabilities, prices, etc., of the required raw materials and components. If firms already have the information at hand in their database, the design decision can be made much more quickly and effectively, so that production can begin without delay. In today's highly competitive market, being the first one to put a new product into the market can bring significant advantages to the firm such as larger market share and a higher profit margin.

Since monitoring processes cost time and money, firms need to determine the right monitoring strategy. For those extremely important suppliers and frequent risk events which can cause severe losses, real-time monitoring is necessary. Periodic monitoring or event-trigger monitoring can be used for other suppliers and events.

### 3.1.2. A risk classification method

Risk management costs time and money. Different risks have different properties and severities. Therefore, different strategies should be adopted based on what kinds of risks firms are facing. Naturally, risk classification needs to precede any risk mitigation.

Risks can be classified from different points of view in different ways as shown in various literatures. From the business strategy point of view, this dissertation proposes the risk classification shown in Figure 3.2.

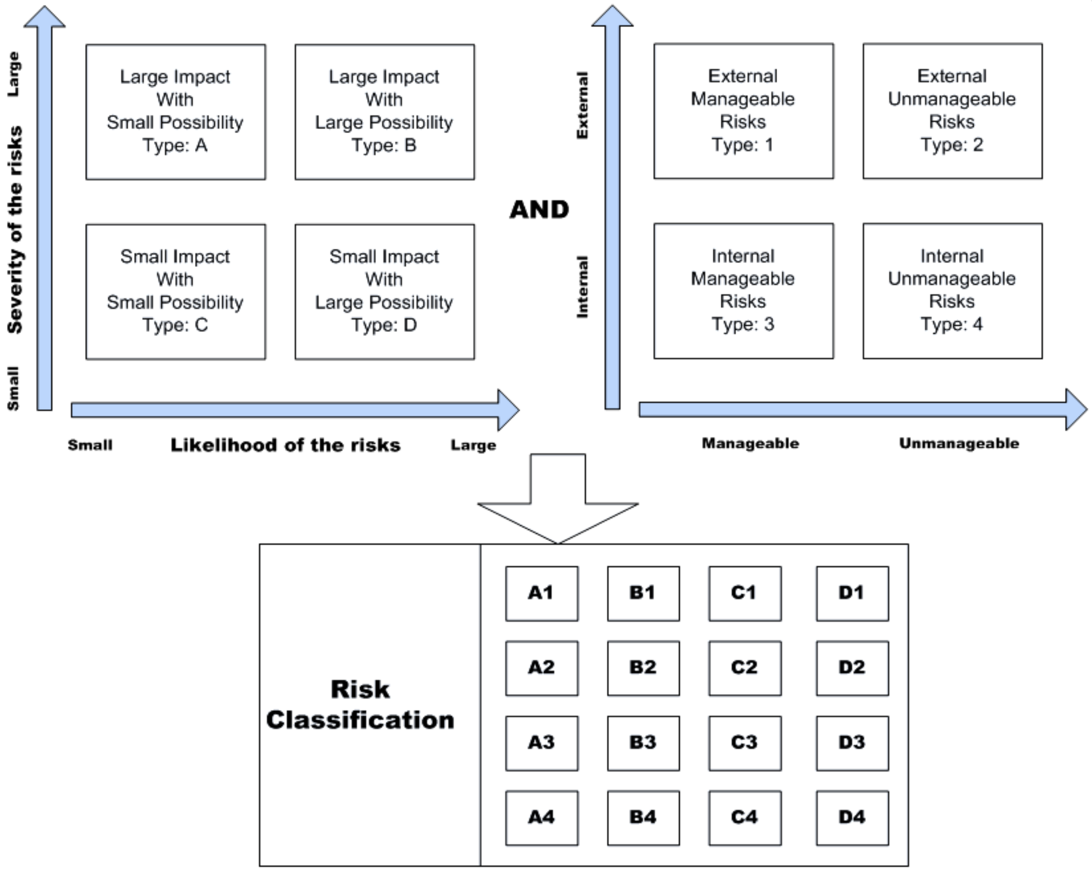


Figure 3.2 Risk classification

Different risks can peoduce different levels of impact on firms. Some of them rarely happen, but others could happen quite often. Risks can originate from inside, including inventory, production, etc., or from outside, including business environment, suppliers, customers, etc. Some of the risks are controllable, such as insufficient inventory; and others are not controllable, such as natural disasters. Thus, risks in supply chains can be classified into 16 categories, as shown in Figure 3.2. Table 3.1 gives one example for each category. The examples for category B1 and category D2 are almost the same, except that firms are adopting a JIT business strategy in the case of B1 but not in the case of D2. This demonstrates that the same event can cause different impacts to firms depending on their business strategies.

**Table 3.1 Examples of risks**

| | **Large Impact & Small Possibility** | **Large Impact & Large Possibility** | **Small Impact & Small Possibility** | **Small Impact & Large Possibility** |
|---|---|---|---|---|
| **External & Manageable** | Bankruptcy of a major supplier | A car accident temporarily causes a traffic jam on a road through which incoming trucks have to pass for a manufacturing facility using JIT | A long-delay customer service phone line operated by a third-party technical service provider in India | Higher than expected defective rate from a T-shirt manufacturer in China which supplies Wal-Mart |
| **External & Unmanageable** | A serious earthquake destroys one of the manufacturing facilities | A car bomb is attached to an American petroleum production facility in Iraq | Product returns from customers | A car accident temporarily causes a traffic jam on a road through which incoming trucks have to pass for a manufacturing facility not using JIT |
| **Internal & Manageable** | Labor strikes | Too many defective products from a newly-built production line with new employees | Breakdown of a machine | Misplacement of an inspection instrument in a hospital |
| **Internal & Unmanageable** | A serious fire in a major warehouse | Miscommunication between engineers in an overseas manufacturing facility and foreign workers caused by language barrier | Defective films from Kodak's production lines | Defective CPUs from Intel's production lines |

### 3.1.3. Risk prioritizing

After risks have been identified and analyzed, firms should already have their lists of risks. With limited resources, firms have to focus on the most important ones. Therefore, risk prioritizing is required before risk mitigation. Firms can develop their own prioritizing methods, or they can adopt some established methods such as subjective risk mapping, the Delphi risk assessment method, and risk scoring methods.

#### Subjective Risk Map

As shown in Figure 3.3, firms can fit the risks on their lists into a 2X2 risk map. Those falling into the top-right corner are the ones that firms should focus on.

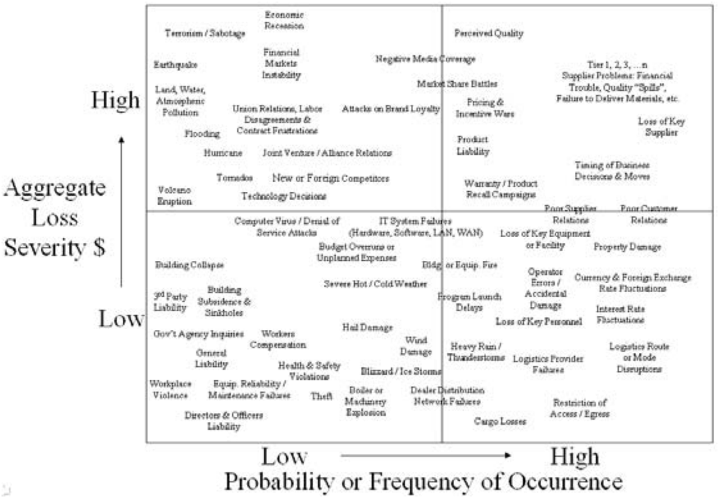


**Figure 3.3 Subjective risk map used by General Motors R&D**

#### Delphi Risk Assessment Method

The Delphi risk assessment method can support two sets of risk assessment processes including prioritizing: 1) the continuous assessment of current risk; and 2) the evaluation of new technology developments or application designs. The Delphi risk assessment method is best used when the opinion of experts is required to support decision making.

#### Risk Scoring Methods

Obtaining a probability distribution for each risk can be very difficult, time consuming, data intensive or impossible if no data exists. Risk scoring methods are used to numerically assign values and prioritize different risks by assessing key factors characterizing each risk.

## 3.2. Risk mitigation and contingency planning

After risk identification, risk analysis, risk prioritizing, and risk classification, firms can begin to mitigate risks. Based on the risk types, corresponding strategies should be applied. Since the risks faced by individual firms are different, there is no one-size-fits-all solution. However, some general recommendations can be made as shown in Figure 3.4.

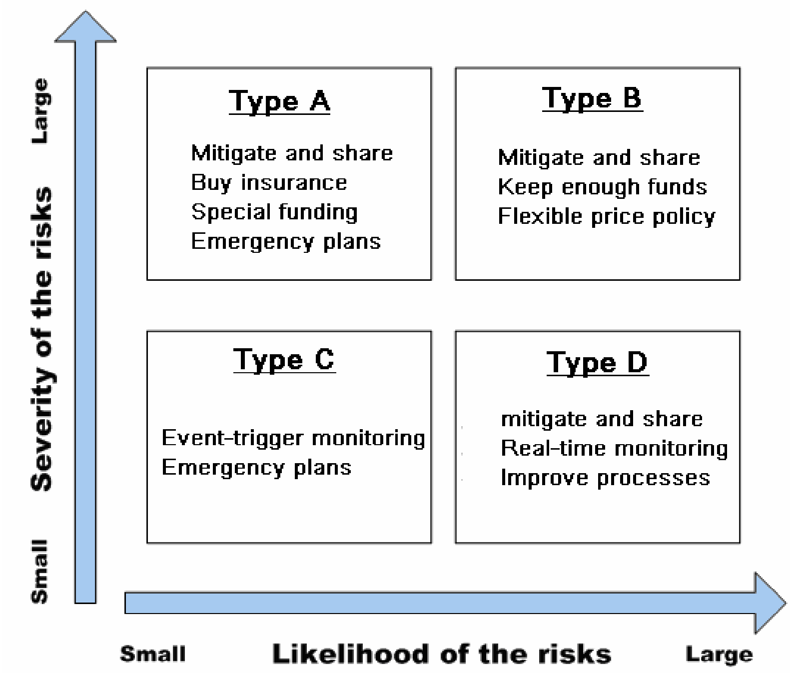


**Figure 3.4 General suggestions for risk mitigation strategies**

Based on risk/cost analysis, firms should be able to reduce or even eliminate some risks. Internal manageable risks are relatively easily handled since firms have much better controls over internal activities. For external manageable risks, collaboration with involved organizations or individuals is required.

As one of the major methods for risk mitigation, contingency plans should be developed for unmanageable risks. If possible, they should be tested in advance to make sure that they will work appropriately when the time comes. Plans should be re-evaluated and updated whenever necessary. For example, suppose that manufacturer A in Canada needs a special type of chip K for its products, and company B in Taiwan is the supplier. On average, A needs 12,000 units of K everyday. Since the inventory cost of K is quite high, A managed to reduce its inventory level to two days, which means that the inventory of K in A’s warehouse is only enough for the production lines to run two days. If A runs out of K, it has to shut down its production lines, and the daily loss will be very high. After realizing that the supply from B could be interrupted by an earthquake, floods, or some other sudden events, A develops a contingency plan which will have company C in Japan as an alternate emergency supplier. A signed a contract with C, which requires C to begin to supply A with at least 8,000 units of K a day no later than 48 hours after notification. However, C charges about 50% higher than the regular price. About one year later, A finds that company D in Thailand has just upgraded its production lines and thus has the ability to produce K, even though this is not its main product. After contacting D, A learns that D can begin to supply A with 10,000 units of K a day no later than 48 hours after notification by A, and C only charges about 25% above the regular price. Obviously, A needs to change its contingency plan and makes D its emergency supplier for chip K. Although C is no longer the emergency supplier, A may still need to continue monitoring C just in case. As a major risk management method, contingency plans are also widely used in other industries such as banking and airlines.

### 3.3. Other important topics related to supply risk management

In this section, three important topics related to supply risk management are discussed.

#### 3.3.1. Information about global suppliers

Data are fundamental for any decision making in supply chains. Firms need to build an information database depending on their needs. Information should be collected following systematic plans and updated promptly. Usually, on the one hand, global suppliers can pose more and more severe risks to the supply chains they join than domestic suppliers. On the other hand, the necessary information about global suppliers is harder to collect than domestic suppliers. This brings high uncertainties to global supply chains. The following are the main resources firms can use to obtain information about global suppliers:

- Publicly available information

  Including stock prices, financial reports, related news and articles in newspapers, magazines and journals, patents, international, regional, and country-specific regulations on exports, etc (Motwani et al.1999).

- Credit rating

  Credit rating shows a company's financial stability, which is an important factor that firms need to consider when selecting strategic suppliers

- Other rating information such as benchmarking scores from other companies
- Business partners' databases

  Firms may be able to get some information about suppliers from their business partners

- Professional service agencies and offices

  There are several government offices where firms may able to find information about suppliers in other countries:

  - Office of the United States Trade Representative, 600 17th Street NW, Washington, DC 20506
  - The United States Trade Commission, 500 E. Street, SW, Washington, DC 20436
  - The American Secretary for Economic and Business Affairs, 2001 C Street NW, Washington, DC 20520
  - United States Mission to the United Nations, 799 United Nations Plaza, New York, NY 10017

- Suppliers themselves

  Firms can directly require information from suppliers, especially potential suppliers. They can visit suppliers without notifying them, ask for references from the suppliers’ other customers, get information about levels of efficiency, speed of delivery, quality, service and complaint handling, check their accounts for any ongoing litigation, etc.

Data sharing mechanisms should be built among business partners. Sharing information about sales, inventory levels, deliveries, etc., in real time can give firms a better idea about what is happening in their supply chains. They can help prevent disruptions. When disruptions do occur, firms can respond as soon as possible to minimize the negative impacts. In this way, risks can be reduced. However, data sharing requires related IT technologies and hardware investments. Not all suppliers can afford expensive solutions. Therefore, different data sharing strategies should be developed for different suppliers. How to keep data confidential is another important topic that needs to be considered.

### 3.3.2. Other sources of supply risks

Supply risks derive not only from procurement, they can also come from other business operations. For example, when designing the interior décor of a new luxury car, designers have different choices. If one design requires a special wooden board in the next five years, and Taiwan is the only place where this kind of wood is available, it might be better to change to another design because it is possible that a war may break out there in the next few years due to some political issues. Another real-world example is provided by Nokia and Ericsson. Both Finland-based Nokia and its prime competitor, Sweden-based Ericsson purchased a critical cellular phone component called radio frequency chips (RFCs) from a Phillips Electronics semiconductor plant in Albuquerque, New Mexico, which caught fire in March 2000. Nokia executives immediately reacted and gave an estimation of the potential impact of this supply crisis: four million cellular handsets would be affected, equivalent to 5% of the company's revenue. Due to their appropriately modularized design, Nokia engineers were able to quickly re-design the RFCs so that the company's other suppliers in Japan and the United States could produce them. Ericsson, which relied exclusively on the Albuquerque plant for the RFCs, reacted much more slowly and its ability to meet customer demand was seriously compromised. It finally posted a nearly $1.7 billion loss for the year, and ultimately had to outsource its cellular handset manufacturing business to another firm.  By contrast, Nokia was able to meet its production goals, and even boost its market share from 27% to 30%. Although some people may think that design and procurement are two totally different business functions, they are actually tightly connected when it pertains to risk management. Therefore, supply risk should be considered in every related business operation and risk management should cover every corner of the business organization.

### 3.3.3. Risks management has no bounds

Although senior mangers and risk managers may have more experience and knowledge to identify, analyze and manage risks, they should not be the only ones involved in risk management. Regular employees should also be encouraged to help because they are much more familiar with their special working areas and therefore are able to identify and reduce certain risks. Suppliers, carriers, and contractors should be involved as well. Through collaboration, they can offer some necessary information such as the kinds of risks they are facing, and the possibilities, frequency and severity of those risks. Some risks associated with connecting activities between buyers and suppliers, which are usually ignored, can also be identified.

A comprehensive risk management board should be formed to guarantee its success. Members should come from different related departments. Regular meetings should be held to review the firm’s ongoing business operations and any related changes such as in the business environment to identify new risks as well as the current control methods for identified risks. The board should also maintain good communication with business partners. Contingency plans should be reviewed and updated whenever necessary.

## 3.4. Research plan

In this section, the research area is defined first and reasons for the selection are given. Techniques that will be used in this research are discussed next, and detailed research plans are introduced at the end.

### 3.4.1. Research area selection

From the discussions above and the literature review in Chapter 2, it is clear that supply risks derive mainly from sudden events and the unsatisfactory performance of suppliers. Most of the sudden events are either uncontrollable or very difficult to predict. Although firms do have some choices to reduce possible loss, such as buying insurance, it is almost impossible for them to eliminate or even reduce the risks themselves. At the same time, most of the risks caused by the unsatisfactory performance of suppliers are controllable, and some of them can even be eliminated. For example, untimely delivery from suppliers is a risk to the buyer. By choosing a supplier with the best delivery performance, this type of risk can be minimized. However, real-world cases usually are not that simple. The supplier with the best delivery performance may charge more for its on-time delivery. Its average defective rate may be also higher than that of the others. If the buyer decides to choose this supplier for better delivery performance, although the risk from unpunctual delivery will be minimized, the risk caused by defective parts becomes severe, and the cost is higher too. Now the question of which supplier(s) should be selected becomes more complicated since it is a multi-criteria optimization problem. Firms need mathematical models to help them to make difficult decisions such as the number they should order from each supplier, considering risks, if there is more than one supplier.

This research focuses on quantitative supply risk management. In other words, this research will develop some mathematical models and tools to help firms make decisions on supplier selection, order quantity, inventory control, transportation mode selection, and production scheduling, taking supply risks into consideration.

### 3.4.2. Technique selection

Following are the major decisions that firms need to make regarding their suppliers considering risks:

- Selecting new suppliers
- Deciding order quantities and delivery times from current suppliers
- Changing suppliers' positions in the current supply base, for example upgrading regular suppliers to strategic suppliers or removing suppliers from the current supply base

As already discussed, many factors including risks need to be considered for the above decisions, and trade-offs on cost and performance have to be made. Traditional qualitative methods will not be sufficient since the problems are very complicated and firms need precise solutions. Therefore, mathematical programming models and methods are the techniques chosen for this research.

The decision philosophy applied in this research is similar to the decision philosophy for investments in the stock market, where the main focus is ***profit vs. risk***. This is quite reasonable because the ultimate objective of business organizations is to maximize profit. From a customer-focused point of view, it can also be deemed as ***value delivered to customers vs. risk***, which is based on the assumption that profit has a positive relationship with the value delivered to customers. Based on this decision philosophy, Multi-Objective Programming (MOP) will be the main optimization tool for this research.

MOP has been used successfully in many areas including facility location, transportation network design, transportation resource allocation, and water resource allocation (Weber and Ellram 1993). MOP deals with optimization problems involving two or more objective functions. In single-objective problems, the goal is to identify the optimal solution, which is a feasible solution giving the best value for the objective function. In multi-objective problems, no solution can optimize all the objectives simultaneously. Trade-offs among objectives have to be made. Certain objectives need to be sacrificed in value in order to obtain an improvement in some other objectives. After defining the trade-offs, certain feasible solutions to the problem can be found such that no other feasible solutions will yield an improvement in one objective without degrading the value of at least one other objective. These feasible solutions are referred to as ***non-inferior***, ***efficient***, ***non-dominated***, or ***Pareto optimal*** solutions. Therefore, in multi-objective problems, the notion of optimal solution is replaced by the concept of ***best compromise solution***, where the best-compromise solution is an efficient solution selected as the preferred alternative by the decision maker.

### 3.4.3. Detailed research plan

Risks have to be quantified before they can be integrated into mathematical models to support decision-making precisely. Therefore, risk quantification is the first research task that needs to be accomplished. Two of the most important decisions that buyers need to make regarding suppliers are: 1) select the best suppliers; 2) order the right quantity of raw materials, components, and/or service at the right time using the right delivery arrangement. Since supplier selection decisions usually are made at the strategic level, development of quantitative models for supplier selection considering risks at the strategic level is the second research task. The last research task is to develop an optimization model to support decision-making at the operational level to determine order quantities, shipment arrangements, production scheduling, etc., considering risks.

#### Task 1: Quantify risks (Chapter 4)

The following steps will be followed.

Step 1. Classify risks into several types based on their characteristics from a mathematical point of view

Step 2. Define a general Risk Function as well as its components using Dr. Taguchi's Loss Function, Step 3. Based on further risk classification, develop more detailed risk functions as well as methods to get the parameters in those functions; some statistical models will be used such as EVT.

Step 4. Develop several risk measures; they can be combined into the strategic supplier selection method and the optimization model at the operational level, which will be developed in later chapters.

Step 5. Give examples to show how to derive the detailed risk functions

**Task 2: Develop a supplier selection method considering risks at the strategic level (Chapter 5)**

The following steps will be followed.

Step 1. Develop a new method to calculate the weights of different criteria to overcome the shortcomings of traditional methods

Step 2. Develop a multi-stage selection method to reduce overall selection difficulties. In the early stages, the new method will guarantee that suppliers will not be eliminated simply because of minor disadvantages in certain aspects compared to other candidates

Step 3. Use an example to show how the method works

**Task 3: Develop a multi-criteria optimization model for operational decisions considering risks (Chapter 6)**

The following steps will be followed.

Step 1. Make necessary modifications to the basic MTOM model which was developed in the author's Master thesis to make the model powerful enough to handle more complicated cases such as unascertained demands, etc.

Step 2. Choose certain risk measures to add to the model describing supply risks quantitatively

Step 3. Rebuild the MTOM model into a multi-criteria optimization model

Step 4. Give an example of the use of the model

The methods and models developed by implementing the above three research tasks can also help firms to make the following decisions:

- **Make/Buy Decisions**. Whether to manufacture certain parts, components, or products by themselves or get them from suppliers or OEMs. Whether to use 3PL providers.
- **Marketing**. The decisions about promotions and other market operations. For example, a big promotion can dramatically increase sales. But if suppliers cannot promptly increase their supplies to satisfy production, a firm’s ability to meet customers’ demand will be seriously compromised.

# Chapter 4

# Risk Quantification

The main purpose of this chapter is to propose a method to quantify supply risks. The definition of risk is introduced first. Then, the similarities and differences between supply risk management and risk management in financial industries are discussed to justify why some models which were developed for risk management in financial industries can be used for risk management in sourcing. Based on the classification of supply risks and the definition of risk, the mathematical description for each component of risk is given or suggested since buyers may come up with their own mathematical models based on the structure proposed by this chapter. The method of using similar external data is also introduced at the end.

## 4.1. Definition of risk

Risk is an elementary part in every aspect of life, and most decisions involve risk. Different types of risks exist in different areas in different forms. The focuses, the purposes, and the methods of handling risks in each area may be different as well. Therefore, a single, agreed set of definitions of risk does not exist. However, in this research, in order to handle risk mathematically, the following definition (Chicken and Posner 1998) is adopted.

$$RISK = Hazard \times Exposure$$

A ***hazard*** is the way in which a thing or situation can cause harm, and harm is used as an all-embracing term that covers financial loss, reputation loss, market share loss, etc. ***Exposure*** is the extent to which the likely recipient of the harm can be influenced by the hazard. It is intended to incorporate the concepts of frequency, probability, and reception. Therefore, unless both hazard and exposure are present simultaneously, there can be no risks. Based on the characteristics of global supply risks, they can be generally classified into two categories for quantification purposes: ***Value-at-Risk (VaR) type*** and ***Miss-the-Target (MtT) type***.

Although risk management is a relatively new topic in supply chain management, its research and application in financial industries have been very intensive in the last several years. Risks in both areas are decided by numerous factors. The VaR-type risk, which is going to be introduced later in this chapter, is very similar to operational risk. Both of them are usually caused by sudden events and, once they happen, they can bring significantly impact firms. The MtT-type risk, which will also be introduced later, is quite similar to the risk in the stock market. Both derive from fluctuations. In the stock market, investors are looking for maximum profit with minimum risk, which actually are two conflicting objectives. When choosing and working with suppliers, firms are doing exactly the same thing. The portfolio approach is the most common strategy adopted by investors in the stock market to reduce risk. It is also used by buyers in supply chains to reduce the risk of single sourcing. Due to the above similarities between risk management in sourcing and risk management in financial industries, it is reasonable to adopt, and modify if necessary, some appropriate risk management models from financial industries and apply them to supply risk management. Therefore, this dissertation proposes to use some of the appropriate mathematical tools, which are widely used in financial industries for risk management, to manage supply risks.

Differences between supply risk management and the risk management used in financial industries must be considered so that necessary modifications can be considered accordingly. One of the major differences is that in financial industries, besides minimizing risk, the only objective is to maximize profit. But in supply chains, buyers usually have many more objectives besides minimizing risk when choosing suppliers. They want high quality products with low prices. They want accurate delivery, excellent customer service, strong product development capabilities, stable financial status, and much more. The other major difference is that the data availability for risk management in financial industries is much greater since risk management has been conducted in financial industries for the past several years while it is still a new research topic in supply chain management.

Data is the basis for mathematical analysis. Based on the availability of risk-related data, buyers may face the following situations:

**Case 1: No data available**

Since there is no data available at all, it is impossible to use mathematical tools to predict the frequencies and severities of the risks. What buyers can do in this case is to try to find all the possible related information and then let experts make a guess based on the collected information and their expertise. For example, computer manufacturer A is planning to have chip manufacturer B, which is in Taiwan, as its major global supplier for the next 10 years. Obviously, A wants to estimate the risks that B can bring to A, and one of the VaR-type risks is the conflict between Taiwan and mainland China. Even though there could be a war in the future, there is no data available such as how serious the damage would be, how long the harbors and airports would be shut down, etc. Therefore, what A can do in this case is to collect all the possible information and then let the experts make a reasonable guess. The military departments and some consulting companies in the US, China, and even Japan have done some simulations about the possible conflicts. Therefore, company A probably can get some valuable information from those departments or consulting companies since they have much more information available about the impacts of conflicts and they are the experts for this specific topic. Then, based on the collected information, and maybe with some external help, senior managers of A can make a reasonable guess. This dissertation does not consider this case.

**Case 2: No direct historical data is available**

Compared to case 1, more data are available although they are not directly related to A. For example, A is a new PC manufacturer in the US market, and is considering having some suppliers from Taiwan. An earthquake is one of the major VaR-type risks A must consider. Since A has never worked with any supplier in Taiwan before, it does not have any direct data available. However, there are a lot of related reports about the impact of the earthquake in Taiwan in 1999 available for A's reference. In this case, although A does not have any direct data in hand, it does have enough external data to make some sound estimates. Besides VaR type risks, A also needs to estimate potential suppliers' MtT-type risks. A can ask them to offer some data from their other customers about delivery accuracy, defective rate, etc., for reference. In this chapter, the methods of using external data for estimation are introduced in the last section.

**Case 3: Direct historical data are available**

In this case, buyers can follow the risk classification and the general risk function proposed in this chapter to come up with their own risk functions based on the direct historical data they possess. They can do some regression analysis to find the distributions fitting their data best, or use the distributions suggested in this chapter.

In the following part of this chapter, the VaR-type risks and MtT-type risks are discussed in detail, and the distributions for the hazard function and the exposure function are proposed mainly for Case 3. Methods describing how to use external date for risk analysis are introduced in the last section.

### 4.2. VaR-type risks

Generally, VaR-type risks are caused by certain events such as earthquakes, floods, fires, regulation changes, wars, sudden departure of key personnel, etc. Usually, those events do not happen frequently. But once they happen, they can create a significant impact on firms or no impact at all. For example, lightning is a normal environmental phenomenon, but a lightning bolt does not hit a building often. In many cases, only minor damage is caused. But, the lightning bolt that hit a semiconductor plant in New Mexico in 2000 cost Ericsson $1.7 billion and changed the landscape of the global cellular telecommunication industry forever (Christopher and Peck 2004). VaR-type risks must be considered and appropriately handled while firms are enjoying the benefits of their global supply chains. These sudden events are hard to predict and it is almost impossible to prevent them from happening. Global suppliers usually pose more VaR-type risks to buyers than do local suppliers. What firms mainly can do is prepare for those risks and try to minimize their impact. While facing operational risks, financial organizations always want to have enough cash or financial assets. Similarly, insurance companies also have to prepare for large claims. On the one hand, if what they have prepared is not enough, they will face serious consequences. On the other hand, if they are over prepared, they may lose opportunities to make more profit by letting the money and assets idle. In the long run, they will lose their competitive advantage to their competitors and may go out of business. Buyers in supply chains are in the same situation. They need to evaluate the VaR-type risks associated with potential suppliers during the selection process and prepare for the VaR-type risks from their current suppliers. It is critical to predict the frequency of VaR-type risks and the severity of their impact so that mitigation/contingency plans can be prepared.

VaR models were developed for the financial industry in the early 1990s, and are considered the standard measure for market risk and used extensively in risk management. From a financial market point of view, VaR measures the maximum possible loss in the market value of a given portfolio that can be expected to occur. In other words, VaR calculates an eventual extreme loss resulting from holding a portfolio for a determined period. VaR has two quantitative parameters, horizon and confidence level. Horizon is the time period for VaR, and ideally, should correspond to the longest period needed for orderly portfolio liquidation. Confidence level depends on its use. If the resulting VaRs are directly used for the choice of a capital cushion, then the choice of the confidence level is crucial, as it should reflect the degree of risk aversion of the company and the cost of a loss exceeding VaR. Higher risk aversion, or greater costs, imply that a greater amount of capital should cover possible losses, thus leading to a higher confidence level. In contrast, if VaR numbers are just used to provide a company-wide yardstick to compare risks across different markets, then the choice of the confidence level is not too important. Naturally, the higher the confidence level, the larger the VaR value will be.

Considering the characteristics of the concept of VaR and the global supply risks caused by sudden events, VaR can be used to quantify those risks. Consider a simple example. Manufacturer A has a chip supplier B in Taiwan and there is a 5% chance that there will be an earthquake within the next 5 years near B's location. With 95% probability, it will reduce B's production capacity to 85%, and the damage to A correspondingly will be \$800,000. In this example, if the hazard value is expressed in terms of money, it equals to \$800,000. The confidence level is 95%, and the time horizon is 5 years. A's exposure to the risk is 0.05. The generalized ***VaR-type risk function*** is:

$$R_{VaR}(E) = H_{VaR} \times P_{VaR}$$

where $H_{VaR}$ denotes the VaR-type hazard to the buyer if event $E$ occurs, and $P_{VaR}$ denotes the extent of the buyer's exposure to the hazard, which is frequency or probability. Intuitively, the unit of hazard is the dollar. However, it can also be something else depending on which aspects firms decide to focus. For example, it can be the percentage of effective production capacities, or customer satisfaction level.

### 4.2.1. VaR-type hazard function

Extreme Value Theory (EVT) is proposed to describe and predict VaR-type hazards for its characteristics and successful application in many industries. EVT has been applied in reliability theory (Lawless 1982), insurance (Embrechts et al. 1997), telecommunications (Gumbel 1958), environmental monitoring (measuring sea levels, pollution concentrations, levels of rives – Embrechts et al. 1997; Gumbel 1958), and more recently finance (Longin 1997). The application of EVT has been particularly important for calculating the probability of events connected to engineering (Davison 1983), such as building a dam.

EVT has the mathematical tools to predict the chances of sudden events even when they have never happened. It is widely used in the financial industries now to predict the operational risks which are quite similar to VaR-type supply risks.

There are three important extreme value distributions defined by Frechet, Gumbel, and Weibull (Castillo et al. 2005). A convenient representation of them is the

Generalized Extreme Value (GEV) distribution, $F_{\lambda,\delta,\kappa}(x)$ with three parameters. It arises as the limit distribution of normalized maxima of independently and identically distributed random variables, and can be represented as follows.

$$F_{\lambda,\delta,\kappa}(x)=\begin{cases}\exp\left\{-\left[1-\kappa\left(\dfrac{x-\lambda}{\delta}\right)\right]^{1/\kappa}\right\}, & 1-\kappa\left(\dfrac{x-\lambda}{\delta}\right)\geq 0,\kappa\neq 0,\\ \exp\left\{-\exp\left(\dfrac{\lambda-x}{\delta}\right)\right\}, & -\infty<x<\infty,\kappa=0.\end{cases}$$

where $\lambda$ is the location parameter, $\delta$ is the scale parameter, and $\kappa$ is the shape parameter. The pdf function is:

$$\begin{cases}f_{\lambda,\delta,\kappa}(x)=\exp\left[-\left[1-\kappa\left(\dfrac{x-\lambda}{\delta}\right)\right]^{1/\kappa}\right]\left[1-\kappa\left(\dfrac{x-\lambda}{\delta}\right)\right]^{1/\kappa-1}\dfrac{1}{\delta} & \kappa\neq 0\\ f_{\lambda,\delta}(x)=\exp\left[-\exp\left(\dfrac{\lambda-x}{\delta}\right)\right]\exp\left(\dfrac{\lambda-x}{\delta}\right)\dfrac{1}{\delta} & \kappa=0\end{cases}$$

When $\kappa\to 0$, GEV distribution is actually Gumbel distribution. GEV distribution is Frechet distribution when $\kappa>0$, and Weibull distribution when $\kappa<0$.

The most used estimation methods for the parameters of GEV are: Moments, Probability Weighted Moments (PWM), and Maximum Likelihood (ML). Although the moments method is the simplest way to estimate parameters, it is also the one with the highest biases, and is not recommended. Since only a small number of data for each VaR type risk are available and the PWM method is less biased than ML for small samples (Coles and Dixon 1998), the PWM method is recommended in the dissertation.

### Probability Weighted Moments

PWM consists of matching moments based on $F_{\lambda,\delta,\kappa}(x)$ to the corresponding empirical moments based on the data in order to estimate $\lambda$, $\delta$, and $\kappa$. Given a random sample of size $n$ from distribution $F_{\lambda,\delta,\kappa}(x)$, estimation of moments is most convenient based on the ordered sample $x_1\leq x_2\leq\cdots\leq x_n$. The statistics

$$b_r = n^{-1}\sum_{i=1}^{n}\frac{(i-1)(i-2)\cdots(i-r)}{(n-1)(n-2)\cdots(n-r)}x_i$$

is an unbiased estimator of moment $r$. The other way to estimate moments is

$$\widehat{\beta}_r[p_{i,n}] = n^{-1}\sum_{i=1}^{n} p_{i,n}^r x_i$$

where $p_{i,n}$ is a plotting position, that is, a distribution-free estimate of $F_{\lambda,\delta,\kappa}(x_i)$. Reasonable choices of $p_{i,n}$, such as

$$p_{i,n} = (i-a)/n, \quad 0 < a < 1 \quad \text{or} \quad p_{i,n} = (i-a)/(n+1-2a), \quad -\frac{1}{2} < a < \frac{1}{2}$$

yield estimator $\widehat{\beta}_r[p_{i,n}]$, which are asymptotically equivalent to $b_r$ and thus, consistent estimators of moments $r$. The purpose of having $a$ here is to create a series of equally spanned points (quantile) in the range of [0, 1], so the observed values can be compared with the values from a similar distribution. Therefore, it does not matter what exact value is chosen for $a$ as long as it can create an equally spanned series of points. A firm can use the estimators suggested by Hosking et al. (1985) as follows to get the parameters.

$$c = \frac{2b_1 - b_0}{3b_2 - b_0} - \frac{\log 2}{\log 3}$$

$$\widehat{\kappa} = 7.859c + 2.9554c^2$$

$$\widehat{\delta} = \frac{(2b_1 - b_0)\widehat{\kappa}}{\Gamma(1+\widehat{\kappa})(1-2^{-\widehat{\kappa}})}$$

$$\widehat{\lambda} = b_0 + \frac{\widehat{\delta}}{\widehat{\kappa}}(\Gamma(1+\widehat{\kappa}) - 1)$$

**Goodness-of-fit test**

There are two major formal tests for extreme value distributions besides graphical tests, the Sherman test and an application of the Kolmogorov-Smirnov statistics. However, users should be aware that both tests tend to overfit. However, they can still provide a rough basis for accepting/rejecting a model.

## Sherman Test

Sherman (1957) proposed a formal test based on the comparison of estimated distribution and observed data. The test uses the series of ordered data denoted by $(X_{n,i})_{i=1,\ldots,N}$. The statistic is computed using the following equation:

$$\Omega_N = \frac{1}{2}\sum_{i=0}^{N}\left|F_{X_n}(X_{n,i+1}) - F_{x_n}(X_{n,i}) - \frac{1}{N+1}\right|$$

where $F_{X_n}(X_{n,0}) = 0$ and $F_{X_n}(X_{n,1}) = 1$. The $\Omega_N$ can be deemed as the distance over the set of distributions, and is asymptotically distributed as a normal distribution with a mean of $[N/(N+1)]^{N+1}$ and a variance approximately of $(2e-5)/e^2N$. A small $\Omega_N$ value suggests that the behavior of extremes is well described by extreme value distribution.

## Kolmogorov-Smirnov Statistics

Kolmogorov-Smirnov Statistics can be used here to check if the data originated from an extreme value distribution. The test was originally proposed by Chandra et al. (1981) for the fitting of a two-parameter (scale and location) distribution; the inclusion of a third parameter (shape) could cause overfitting. The test steps are:

1) Put the observations in ascending order $y_1 < \ldots < y_n$.
2) Calculate $F(y_i)$, $i = 1,\ldots,n$, where $F(y)$ is the GEV using the estimated parameters
3) Calculate the statistics $D^+$, $D^-$, $D$, and $V$:

$$D^+ = \max_i\left\{\frac{i}{n} - F(y_i)\right\}$$

$$D^- = \max_i\left\{F(y_i) - \frac{i-1}{n}\right\}$$

$$D = \max(D^+, D^-)$$

$$V = D^+ + D^-$$

4) Compare the test statistics multiplied by $\sqrt{n}$ with the values in Table 4.1. The null hypothesis (the data are from GEV) should be rejected at level $\alpha$ if all the statistics exceed the corresponding entry in Table 4.1.

**Table 4.1 Percentage points of statistics $\sqrt{n}D^{+}$, $\sqrt{n}D^{-}$, $\sqrt{n}D$ and $\sqrt{n}V$**

| | | Upper Tail Significance Level $\alpha$ | | | |
|---|---|---|---|---|---|
| **Statistics** | N | 0.10 | 0.05 | 0.025 | 0.01 |
| $\sqrt{n}D^{+}$ | 10 | 0.685 | 0.755 | 0.842 | 0.897 |
| | 12 | 0.694 | 0.764 | 0.848 | 0.907 |
| | 20 | 0.710 | 0.780 | 0.859 | 0.926 |
| | 50 | 0.727 | 0.796 | 0.870 | 0.940 |
| | ∞ | 0.733 | 0.808 | 0.877 | 0.957 |
| $\sqrt{n}D^{-}$ | 10 | 0.700 | 0.766 | 0.814 | 0.892 |
| | 12 | 0.708 | 0.773 | 0.824 | 0.904 |
| | 20 | 0.715 | 0.785 | 0.843 | 0.926 |
| | 50 | 0.724 | 0.796 | 0.860 | 0.944 |
| | ∞ | 0.733 | 0.808 | 0.877 | 0.957 |
| $\sqrt{n}D$ | 10 | 0.760 | 0.819 | 0.880 | 0.944 |
| | 12 | 0.767 | 0.827 | 0.889 | 0.954 |
| | 20 | 0.779 | 0.843 | 0.907 | 0.973 |
| | 50 | 0.790 | 0.856 | 0.922 | 0.988 |
| | ∞ | 0.803 | 0.874 | 0.939 | 1.007 |
| $\sqrt{n}V$ | 10 | 1.287 | 1.381 | 1.459 | 1.535 |
| | 12 | 1.301 | 1.399 | 1.476 | 1.558 |
| | 20 | 1.323 | 1.428 | 1.509 | 1.600 |
| | 50 | 1.344 | 1.428 | 1.538 | 1.639 |
| | ∞ | 1.372 | 1.477 | 1.557 | 1.671 |

Source: Chandra et al. (1981)

### 4.2.2. VaR-type exposure function

The exposure functions for VaR-type risks are actually the probability or frequency functions. With historical data in hand, firms can do some regression analysis at first and then come up with their special distribution functions, or simply try to estimate $\lambda$ for the Poisson distribution suggested by this chapter. The Poisson distribution is a very simple distribution with a lot of nice properties including memoryless. It is widely used in financial industries to fit various risk-related data.

The Poisson distribution is named after the French mathematician and physicist Simeon Denis Poisson. The Poisson distribution has a probability mass function:

$$p_k = \frac{e^{-\lambda}\lambda^k}{k!} \qquad k = 0, 1, 2, ...$$

The cumulative function (step function) is given by:

$$F(x) = e^{-\lambda t}\sum_{i=0}^{\lfloor x \rfloor}\frac{(\lambda t)^i}{i!}$$

The maximum likelihood estimator of $\lambda$ is

$$\hat{\lambda} = \bar{x}$$

where $\bar{x}$ is the sample mean.

### 4.2.3. VaR type risk

After deriving both the hazard function and the exposure function, the next step is to combine them into one aggregated risk distribution which allows buyers to describe and predict VaR-type risk based on the definition of the risk introduced at the beginning of this chapter. However, this kind of aggregation is almost impossible to do analytically (Cruz 2002). There are quite a few solutions for this problem such as applying fast Fourier transforms to the distributions. The simplest method is to do a simulation which actually is a structured scenario analysis. Based on the distributions that users are trying to aggregate, the computation difficulties are quite different. Example 4.1 shows how to get the VaR-type hazard function and the VaR-type exposure function, and then how to aggregate them to get the final VaR-type risk function, which actually is a distribution table.

**Example 4.1**

Computer manufacture A in the US wants to evaluate the risks from its supplier B in the Southern China. Flooding is one of the major problems threatening B due to its location. In the last 10 years, floods have forced B to shut down at least part of its production lines several times for from several days to 2 weeks. In several other years, although B managed to continue its production, finished components could not be shipped out at the scheduled time with the desired quantity to A because either the outgoing road was blocked by flooding or the nearby airport was forced to close. Correspondingly, A suffers severer losses since B is a major supplier to A. Senior mangers of A finally decided to solve the problem. Basically, they have two options. The first one is to buy business insurance for it, and the second option is to decrease B's weight in A's supply base. The problem with the first option is the insurance premium. A received quotes from several insurance companies and the premiums are quite high. For the second option, since the combination of cost and quality that B can offer is the best in its industry, the weight changes will definitely increase the cost and/or affect the quality. In order to make the final decision, A have to evaluate the risks from B precisely and the risk of flooding is a major one.

**VaR-type hazard function**

**Table 4.2 Losses caused by flood from 1996-2005**

| Year | Number of floods | Loss |
|---|---|---|
| 1996 | 1 | $734,900 |
| 1997 | 2 | $580,070 |
| | | $354,180 |
| 1998 | 0 | |
| 1999 | 1 | $457,820 |
| 2000 | 4 | $258,410 |
| | | $1250,000 |
| | | $780,540 |
| | | $243,000 |
| 2001 | 0 | |
| 2002 | 3 | $1358,110 |
| | | $981,250 |
| | | $548,270 |
| 2003 | 4 | $254,170 |
| | | $158,970 |
| | | $987,410 |
| | | $578,940 |
| 2004 | 0 | |
| 2005 | 1 | $875,240 |

Table 4.2 shows A's losses due to 16 floods around B's location in the last ten years. Table 4.3 shows how to calculate $\widehat{\beta}_r$ using plotting position

$$p_{i,n} = \frac{i-0.5}{n}$$

$a$ is set to 0.5 here to create a series of equally spanned points (quantile).

**Table 4.3 Calculating the moment estimators**

| Index | | Plot posi | | Plot posi$^2$ | |
|---|---|---|---|---|---|
| 1 | 158970 | 0.03125 | 4967.8125 | 0.000976563 | 155.2441406 |
| 2 | 243000 | 0.09375 | 22781.25 | 0.008789063 | 2135.742188 |
| 3 | 254170 | 0.15625 | 39714.0625 | 0.024414063 | 6205.322266 |
| 4 | 258410 | 0.21875 | 56527.1875 | 0.047851563 | 12365.32227 |
| 5 | 354180 | 0.28125 | 99613.125 | 0.079101563 | 28016.19141 |
| 6 | 457820 | 0.34375 | 157375.625 | 0.118164063 | 54097.87109 |
| 7 | 548270 | 0.40625 | 222734.6875 | 0.165039063 | 90485.9668 |
| 8 | 578940 | 0.46875 | 271378.125 | 0.219726563 | 127208.4961 |
| 9 | 580070 | 0.53125 | 308162.1875 | 0.282226563 | 163711.1621 |
| 10 | 734900 | 0.59375 | 436346.875 | 0.352539063 | 259080.957 |
| 11 | 780540 | 0.65625 | 512229.375 | 0.430664063 | 336150.5273 |
| 12 | 875240 | 0.71875 | 629078.75 | 0.516601563 | 452150.3516 |
| 13 | 981250 | 0.78125 | 766601.5625 | 0.610351563 | 598907.4707 |
| 14 | 987410 | 0.84375 | 833127.1875 | 0.711914063 | 702951.0645 |
| 15 | 1250000 | 0.90625 | 1132812.5 | 0.821289063 | 1026611.328 |
| 16 | 1358110 | 0.96875 | 1315669.063 | 0.938476563 | 1274554.404 |
| | $b_0$ | | $b_1$ | | $b_2$ |
| | 650080.00 | | 425569.96 | | 320924.21 |

Then,

$$c = \frac{2b_1 - b_0}{3b_2 - b_0} - \frac{\log 2}{\log 3} = 0.0120656194$$

$$\hat{\kappa} = 7.859c + 2.9554c^2 = 0.09525395$$

$$\hat{\delta} = \frac{(2b_1 - b_0)\hat{\kappa}}{\Gamma(1+\hat{\kappa})(1-2^{-\hat{\kappa}})} = 314478.6741$$

$$\hat{\lambda} = b_0 + \frac{\hat{\delta}}{\hat{\kappa}}(\Gamma(1+\hat{\kappa}) - 1) = 495901.0491$$

Since $\kappa \neq 0$,

$$F_{\lambda,\delta,\kappa}(x) = \exp\left\{-\left[1-\kappa\left(\frac{x-\lambda}{\delta}\right)\right]^{1/\kappa}\right\}$$

$$= \exp\left\{-\left[1-0.09525395\left(\frac{x-495901.0491}{314478.6741}\right)\right]^{1/0.09525395}\right\}$$

Kolmogorov-Smirnov Statistics are used in this example for the fitness test. Table 4.4 shows the $F_{\lambda,\delta,\kappa}(x)$, $\frac{i}{n}-F(x_i)$, and $F(x_i)-\frac{i-1}{n}$ values from the original data.

**Table 4.4 Fitness test**

| Index | Loss $x$ | $F_{\lambda,\delta,\kappa}(x)$ | $\frac{i}{n}-F(x_i)$ | $F(x_i)-\frac{i-1}{n}$ |
|---|---|---|---|---|
| 1 | 158970 | 0.062431 | 6.92826E-05 | 0.062430717 |
| 2 | 243000 | 0.11414 | 0.010859683 | 0.051640317 |
| 3 | 254170 | 0.122483 | 0.065016977 | -0.002516977 |
| 4 | 258410 | 0.125738 | 0.124261775 | -0.061761775 |
| 5 | 354180 | 0.211264 | 0.101236413 | -0.038736413 |
| 6 | 457820 | 0.323697 | 0.051303025 | 0.011196975 |
| 7 | 548270 | 0.429355 | 0.008145022 | 0.054354978 |
| 8 | 578940 | 0.465174 | 0.034825995 | 0.027674005 |
| 9 | 580070 | 0.466486 | 0.096014067 | -0.033514067 |
| 10 | 734900 | 0.634863 | -0.009863226 | 0.072363226 |
| 11 | 780540 | 0.678354 | 0.009145668 | 0.053354332 |
| 12 | 875240 | 0.757554 | -0.007554354 | 0.070054354 |
| 13 | 981250 | 0.8283 | -0.015800234 | 0.078300234 |
| 14 | 987410 | 0.831854 | 0.04314599 | 0.01935401 |
| 15 | 1250000 | 0.936387 | 0.001113057 | 0.061386943 |
| 16 | 1358110 | 0.959168 | 0.040831608 | 0.021668392 |

Then,

$$\sqrt{n}D^{+}=\sqrt{16}\max_{i}\left\{\frac{i}{n}-F(x_i)\right\}=4\times 0.124261775=0.497$$

$$\sqrt{n}D^{-}=\sqrt{16}\max_{i}\left\{F(x_i)-\frac{i-1}{n}\right\}=4\times 0.078300234=0.313$$

$$\sqrt{n}D=\sqrt{16}\max(D^{+},D^{-})=4\times 0.124261775=0.497$$

$$\sqrt{n}V=\sqrt{16}(D^{+}+D^{-})=4\times 0.202562009=0.810$$

From Table 4.1, we can conclude that there is no evidence to reject the GEV model.

## VaR-type exposure function

Based on the number of floods each year from Table 4.2, we can estimate the parameter for the VaR-type exposure function (Poisson distribution)

$$\hat{\lambda} = \bar{x} = 1.6$$

## VaR-type risk function

In order to get the final VaR-type risk function, we need to aggregate the hazard function $F_{495901.0491,314478.6741,0.09525}(x)$ and the exposure function $P(1.6)$. As introduced before, it is important to get a close form for this kind of aggregated function. Therefore, the following steps are used to get the risk distribution table into an Excel spreadsheet as shown in Table 4.5.

step 1. Generate Poisson random numbers with $\lambda = 1.6$ in the second column of the spreadsheet (the first column is used to count the number of runs, and the number of runs should be large enough such as 10,000 or 1000,000 times. However, in this example, in order to show the whole table, only 100 runs are conducted)

step 2. Generate as many uniform random variables as demanded by the frequency (numbers in the second column) and use them as the probabilities

step 3. Based on generated probabilities, determine the corresponding $x$ value from the GEV distribution

step 4. Sum up all the results in a new column, total.

**Table 4.5 Using Excel Spreadsheet to get the risk distribution**

| Run # | FREQUENCY | 1 | First Event | 2 | Second Event | 3 | Third Event | 4 | Fourth Event | 5 | Fifth Event | 6 | Sixth Event | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | | | | | | | | | | | | 0 |
| 2 | 3 | 0 | 489250 | 0 | 508046 | 1 | 797556 | | | | | | | 1794852 |
| 3 | 1 | 1 | 867520 | | | | | | | | | | | 867520 |
| 4 | 0 | | | | | | | | | | | | | 0 |
| 5 | 0 | | | | | | | | | | | | | 0 |
| 6 | 0 | | | | | | | | | | | | | 0 |
| 7 | 1 | 1 | 1493229 | | | | | | | | | | | 1493229 |
| 8 | 1 | 1 | 1069418 | | | | | | | | | | | 1069418 |
| 9 | 1 | 1 | 773856 | | | | | | | | | | | 773856 |
| 10 | 3 | 0 | 566584 | 1 | 832807 | 0 | 382004 | | | | | | | 1781395 |
| 11 | 0 | | | | | | | | | | | | | 0 |
| 12 | 3 | 1 | 1257954 | 0 | 419163 | 1 | 846171 | | | | | | | 2523289 |
| 13 | 2 | 1 | 1444241 | 1 | 889247 | | | | | | | | | 2333488 |
| 14 | 0 | | | | | | | | | | | | | 0 |
| 15 | 2 | 1 | 1143845 | 1 | 752208 | | | | | | | | | 1896053 |
| 16 | 0 | | | | | | | | | | | | | 0 |
| 17 | 0 | | | | | | | | | | | | | 0 |
| 18 | 0 | | | | | | | | | | | | | 0 |
| 19 | 4 | 0 | 500345 | 1 | 699525 | 0 | 471877 | 1 | 694979 | | | | | 2366726 |
| 20 | 2 | 1 | 990232 | 0 | 130547 | | | | | | | | | 1120779 |
| 21 | 3 | 0 | 180652 | 0 | 431397 | 1 | 1225999 | | | | | | | 1838048 |
| 22 | 4 | 0 | 405616 | 0 | 357071 | 0 | 96802 | 1 | 637749 | | | | | 1497237 |
| 23 | 1 | 0 | 523134 | | | | | | | | | | | 523134 |
| 24 | 6 | 0 | 469712 | 0 | 449611 | 1 | 1250405 | 0 | 476475 | 1 | 996437 | 1 | 1489980 | 5132621 |
| 25 | 1 | 0 | 157818 | | | | | | | | | | | 157818 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 4 | 0 | 366960 | 0 | 347183 | 0 | 521843 | 1 | 770985 | | | | | 2006971 |
| 27 | 1 | 1 | 779759 | | | | | | | | | | | 779759 |
| 28 | 1 | 0 | 550667 | | | | | | | | | | | 550667 |
| 29 | 2 | 1 | 796500 | 0 | 455325 | | | | | | | | | 1251826 |
| 30 | 0 | | | | | | | | | | | | | 0 |
| 31 | 2 | 0 | 350247 | 1 | 1961038 | | | | | | | | | 2311285 |
| 32 | 5 | 1 | 1135994 | 0 | 432748 | 1 | 1623082 | 1 | 730695 | 0 | 409341 | | | 4331860 |
| 33 | 3 | 0 | 550213 | 1 | 638193 | 1 | 937760 | | | | | | | 2126165 |
| 34 | 1 | 0 | 25071 | | | | | | | | | | | 25071 |
| 35 | 1 | 1 | 768509 | | | | | | | | | | | 768509 |
| 36 | 1 | 1 | 769862 | | | | | | | | | | | 769862 |
| 37 | 2 | 1 | 1031770 | 0 | 551555 | | | | | | | | | 1583325 |
| 38 | 6 | 1 | 797858 | 1 | 703080 | 1 | 779267 | 0 | 115436 | 0 | 550968 | 1 | 951443 | 3898051 |
| 39 | 2 | 0 | 499559 | 1 | 729583 | | | | | | | | | 1229143 |
| 40 | 3 | 0 | 428273 | 1 | 965858 | 0 | 111070 | | | | | | | 1505201 |
| 41 | 2 | 0 | 601212 | 0 | 431424 | | | | | | | | | 1032636 |
| 42 | 1 | 1 | 901385 | | | | | | | | | | | 901385 |
| 43 | 5 | 1 | 1026362 | 1 | 862099 | 0 | 534473 | 0 | 287464 | 1 | 810410 | | | 3520809 |
| 44 | 5 | 1 | 812262 | 0 | 291132 | 0 | 280948 | 1 | 887382 | 0 | 383284 | | | 2655008 |
| 45 | 0 | | | | | | | | | | | | | 0 |
| 46 | 2 | 0 | 532718 | 1 | 1393997 | | | | | | | | | 1926715 |
| 47 | 3 | 1 | 852425 | 0 | 55445 | 1 | 1030319 | | | | | | | 1938188 |
| 48 | 2 | 0 | 307742 | 0 | 449843 | | | | | | | | | 757585 |
| 49 | 2 | 0 | 336367 | 0 | 548786 | | | | | | | | | 885153 |
| 50 | 1 | 0 | 491213 | | | | | | | | | | | 491213 |
| 51 | 3 | 0 | 543767 | 0 | 502719 | 1 | 895265 | | | | | | | 1941751 |
| 52 | 2 | 1 | 759969 | 0 | 535499 | | | | | | | | | 1295468 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 53 | 2 | 0 | 506531 | 0 | 200338 | | | | | | | 706869 |
| 54 | 4 | 0 | 476596 | 1 | 692923 | 0 | 562684 | 0 | 327759 | | | 2059962 |
| 55 | 2 | 1 | 800643 | 0 | 481165 | | | | | | | 1281809 |
| 56 | 0 | | | | | | | | | | | 0 |
| 57 | 1 | 0 | 602216 | | | | | | | | | 602216 |
| 58 | 2 | 0 | 0 | 0 | 476911 | | | | | | | 476911 |
| 59 | 0 | | | | | | | | | | | 0 |
| 60 | 3 | 0 | 530002 | 0 | 471462 | 0 | 193904 | | | | | 1195368 |
| 61 | 5 | 0 | 536921 | 1 | 1076430 | 1 | 1190305 | 0 | 526238 | 0 | 513884 | 3843777 |
| 62 | 2 | 0 | 405161 | 1 | 909722 | | | | | | | 1314882 |
| 63 | 1 | 0 | 429708 | | | | | | | | | 429708 |
| 64 | 1 | 1 | 1509111 | | | | | | | | | 1509111 |
| 65 | 2 | 1 | 673327 | 0 | 417864 | | | | | | | 1091191 |
| 66 | 3 | 0 | 231378 | 1 | 614282 | 1 | 1172300 | | | | | 2017960 |
| 67 | 0 | | | | | | | | | | | 0 |
| 68 | 2 | 0 | 454116 | 1 | 978471 | | | | | | | 1432587 |
| 69 | 3 | 1 | 878859 | 1 | 1260816 | 1 | 1095962 | | | | | 3235638 |
| 70 | 2 | 1 | 638091 | 1 | 692892 | | | | | | | 1330984 |
| 71 | 1 | 1 | 1109613 | | | | | | | | | 1109613 |
| 72 | 1 | 1 | 821346 | | | | | | | | | 821346 |
| 73 | 0 | | | | | | | | | | | 0 |
| 74 | 0 | | | | | | | | | | | 0 |
| 75 | 4 | 1 | 829684 | 1 | 870005 | 1 | 708273 | 0 | 282534 | | | 2690496 |
| 76 | 2 | 0 | 328794 | 0 | 477147 | | | | | | | 805942 |
| 77 | 0 | | | | | | | | | | | 0 |
| 78 | 1 | 0 | 413228 | | | | | | | | | 413228 |
| 79 | 1 | 0 | 200436 | | | | | | | | | 200436 |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 2 | 0 | 344866 | 0 | 557911 |  |  |  |  | 902777 |
| 81 | 1 | 0 | 180416 |  |  |  |  |  |  | 180416 |
| 82 | 0 |  |  |  |  |  |  |  |  | 0 |
| 83 | 2 | 0 | 340673 | 1 | 862625 |  |  |  |  | 1203298 |
| 84 | 0 |  |  |  |  |  |  |  |  | 0 |
| 85 | 0 |  |  |  |  |  |  |  |  | 0 |
| 86 | 2 | 1 | 904541 | 0 | 398664 |  |  |  |  | 1303204 |
| 87 | 1 | 1 | 674269 |  |  |  |  |  |  | 674269 |
| 88 | 0 |  |  |  |  |  |  |  |  | 0 |
| 89 | 2 | 1 | 1073225 | 0 | 215273 |  |  |  |  | 1288498 |
| 90 | 3 | 1 | 637766 | 1 | 863776 | 0 | 252447 |  |  | 1753989 |
| 91 | 3 | 0 | 114441 | 0 | 387754 | 1 | 1980936 |  |  | 2483131 |
| 92 | 1 | 0 | 191941 |  |  |  |  |  |  | 191941 |
| 93 | 0 |  |  |  |  |  |  |  |  | 0 |
| 94 | 3 | 0 | 338280 | 0 | 492071 | 1 | 902091 |  |  | 1732442 |
| 95 | 2 | 1 | 844208 | 1 | 790460 |  |  |  |  | 1634668 |
| 96 | 2 | 0 | 511734 | 0 | 561077 |  |  |  |  | 1072811 |
| 97 | 1 | 0 | 320535 |  |  |  |  |  |  | 320535 |
| 98 | 4 | 0 | 501798 | 1 | 978809 | 0 | 492029 | 1 | 614862 | 2587499 |
| 99 | 3 | 1 | 1060908 | 1 | 657276 | 1 | 1082388 |  |  | 2800572 |
| 100 | 2 | 1 | 818099 | 1 | 1197865 |  |  |  |  | 2015964 |

In Table 4.5, for a certain probability, the corresponding $x$ from the GEV distribution is:

$$x = \frac{\delta(1-(-\ln p)^{\kappa})}{\kappa} + \lambda$$

From Table 4.5, the distribution for the VaR-type risk caused by flood can be computed as shown in Table 4.6.

**Table 4.6 VaR-type risk distribution (in dollars)**

| Quantile | Risk | Quantile | Risk | Quantile | Risk | Quantile | Risk |
|---|---|---|---|---|---|---|---|
| 99% | 5132621 | 74% | 1794852 | 49% | 1069418 | 24% | 180416 |
| 98% | 4331860 | 73% | 1781395 | 48% | 1032636 | 23% | 157818 |
| 97% | 3898051 | 72% | 1753989 | 47% | 902777 | 22% | 25071 |
| 96% | 3843777 | 71% | 1732442 | 46% | 901385 | 21% | 0 |
| 95% | 3520809 | 70% | 1634668 | 45% | 885153 | 20% | 0 |
| 94% | 3235638 | 69% | 1583325 | 44% | 867520 | 19% | 0 |
| 93% | 2800572 | 68% | 1509111 | 43% | 821346 | 18% | 0 |
| 92% | 2690496 | 67% | 1505201 | 42% | 805942 | 17% | 0 |
| 91% | 2655008 | 66% | 1497237 | 41% | 779759 | 16% | 0 |
| 90% | 2587499 | 65% | 1493229 | 40% | 773856 | 15% | 0 |
| 89% | 2523289 | 64% | 1432587 | 39% | 769862 | 14% | 0 |
| 88% | 2483131 | 63% | 1330984 | 38% | 768509 | 13% | 0 |
| 87% | 2366726 | 62% | 1314882 | 37% | 757585 | 12% | 0 |
| 86% | 2333488 | 61% | 1303204 | 36% | 706869 | 11% | 0 |
| 85% | 2311285 | 60% | 1295468 | 35% | 674269 | 10% | 0 |
| 84% | 2126165 | 59% | 1288498 | 34% | 602216 | 9% | 0 |
| 83% | 2059962 | 58% | 1281809 | 33% | 550667 | 8% | 0 |
| 82% | 2017960 | 57% | 1251826 | 32% | 523134 | 7% | 0 |
| 81% | 2015964 | 56% | 1229143 | 31% | 491213 | 6% | 0 |
| 80% | 2006971 | 55% | 1203298 | 30% | 476911 | 5% | 0 |
| 79% | 1941751 | 54% | 1195368 | 29% | 429708 | 4% | 0 |
| 78% | 1938188 | 53% | 1120779 | 28% | 413228 | 3% | 0 |
| 77% | 1926715 | 52% | 1109613 | 27% | 320535 | 2% | 0 |
| 76% | 1896053 | 51% | 1091191 | 26% | 200436 | 1% | 0 |
| 75% | 1838048 | 50% | 1072811 | 25% | 191941 | 0% | 0 |

Following are several important issues related to the risk table achieved by the above method:

- The values in the above table are associated with a certain time unit, and the time unit in this example is a year. This means that, with 95% confidence, the annual loss from flood will not be larger than $3,520,809. Depending on the method that buyers use for collecting and processing the original data, the time unit could also be a month, 10 years, etc.

- The values directly from above table are the values corresponding to certain quantile. In many cases, firms may be more interested in getting the expected value instead of “maximum possible” type of values. Approximately, the expected value is the average of the risk values in the above table.

### 4.3. Miss-the-Target (MtT)-type risks

Based on buyers’ own needs, they have certain target values for certain measures for suppliers to reach. For example, manufacture A wants its supplier B’s trucks to come in three times a day exactly at 6:00AM, 2:00PM, and 10:00PM. A is running JIT and only keeps very little stock for emergency. Therefore, delay is costly because shutting down production lines for out-of-component stock can cause A thousands of dollars per second. Since other suppliers of A also have trucks coming in every day, and A’s delivery trucks also come out several times a day, early arrivals of B’s trucks can also cause problems since they can block the way. A also expects that the defective rate of B’s components is 0, and B is willing to take 100% responsibility for over-ordered components. In this example, the target values for delivery time are 6:00AM, 2:00PM, and 10:00PM. The target value for defective rate is 0, and the target value for B’s responsibility for over-ordered components is 100%. However, due to various reasons (excluding the sudden events which cause the VaR-type risks), B may not always be able to make the targets. In a lot of cases, its trucks arrive at A’s facility early because the drivers are afraid that they are going to be late. In other cases, the trucks are late due to heavy traffic. Some defective components are sent to A once in a while since it is not economically possible for B to check every component before sending them out. Components can also be damaged on their way to A. For the over-ordered components, B agrees to take the responsibility for some of them. The percentage keeps changing and depends on the received orders from other customers, the over-ordered quantity, etc. Because B cannot always make the targets, some problems can be caused to A. The ahead-of-schedule trucks may block the way of A's delivery trucks to its distribution centers and trucks from other suppliers. Defective components can slow down A's production if A is lucky to detect them on its production lines. If A's products with B's defective components are sold to customers, the expensive customer returns will be caused. If B is unwilling to take the full responsibility for the over-ordered components, A has to pay for the inventory cost.

The above example shows that suppliers' missing the targets, which are set by the buyers, can cause losses. In other words, buyers are facing the risks from their suppliers for missing the targets of delivery time, defective rate, etc. This type of risk is called ***MtT-type***. Compared to VaR-type risks, MtT-type risks happen frequently. They can be controlled, but may not be totally eliminated for economical reasons. The impacts to buyers are usually not as dramatic as VaR-type risks considering each single case. However, in the long run, the accumulated impacts can also be significant. Usually, the further the actual value is away from the target value, the larger the hazard that will be brought to the buyers.

Different suppliers miss the targets in different ways as shown in Figure 4.1. Sometimes they can make it and sometimes they are far away. Some suppliers can make the target more often than others. In other words, different suppliers may have different probabilities to achieve the target value.

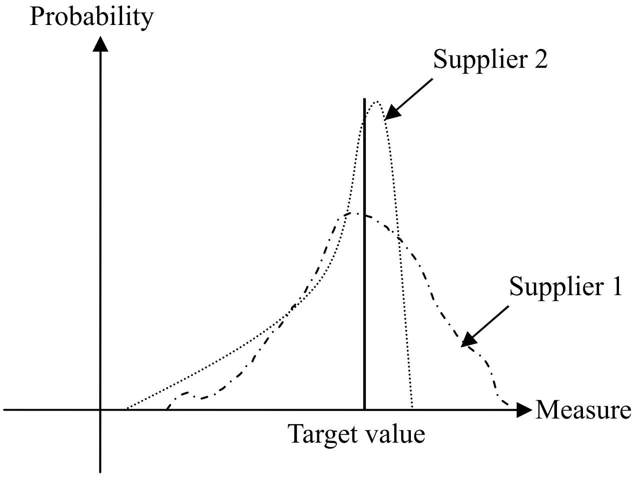


**Figure 4.1 Performance of different suppliers**

For example, as shown in Figure 4.2, supplier B has a 90% chance to make on-time delivery, a 5% chance to be late within 6 hours and a 3% chance to be late more than 6 hours but within 24 hours, and a 2% possibility to be later more than 24 hours. In Figure 4.2, area 1 equal 5%, area 2 equals 3%, and area 3 equals 2%.

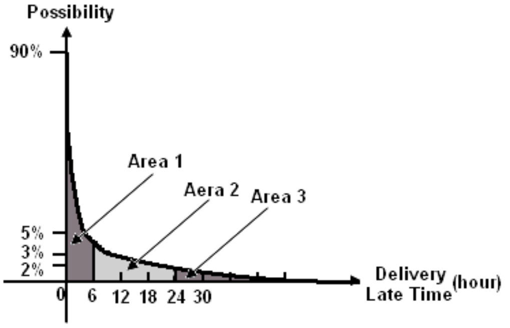


**Figure 4.2 Possibility curve of supplier B's delivery performance**

In general, the MtT-type risk function can be defined as follows:

$$R_{MtT}(X, x_0) = H_{MtT} \times P_{MtT}$$

where $X$ stands for the certain measure that the buyer is concerned with. $x_0$ stands for the target value set by the buyer. $H_{MtT}$ is the hazard which exists because the target value cannot always be reached. $P_{MtT}$ stands for the buyer's exposure to the hazard $H_{MtT}$.

Depending on the measure and the way the buyer sets the target value, suppliers' actual performance could always be lower than the target value, higher than the target value, or fluctuate around the target value. Therefore, MtT-type can be further categorized as S-type, N-type, and L-type.

### 4.3.1. MtT type hazard function

Since buyers have all the necessary data to calculate how serious the impact will be for certain performance of the suppliers, the MtT-type hazard function can be achieved with fixed parameters, and the only variable is the difference between the supplier's actual performance and the target. Let $x$ stand for the supplier's actual performance regarding a certain measure, and $\Delta x = x - x_0$. Using Taguchi's loss function, the general S-Type, N-type, and L-type hazard functions are introduced below.

**S-Type**

S-type means the smaller the better. In this case, manufacturer A set the target value for the defective rate to be 0, which means that the best that supplier B can do is to reach the target, and there is no way that B can perform better than A's expectation. Frequently, B cannot make the target. Naturally, the higher the defective rate, the worse the impact that will be brought to A. Following is the general S-type hazard function.

$$H_{MtT-S} = \begin{cases} 0 & X_0 \le x < r_1^+ \\ a^+(x - X_0)^2 + c^+ & r_1^+ \le x \le r_2^+ \\ M^+ & r_2^+ < x \end{cases}$$

where $a^+$ and $c^+$ are hazard parameters, and $M^+$ is the maximum possible loss in the worse case. Figure 4.3 shows the general S-type hazard function

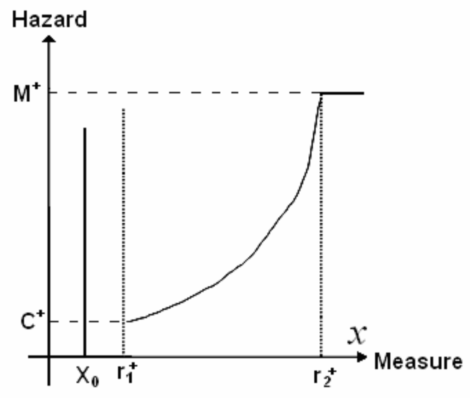


**Figure 4.3 The general S-type hazard function**

### N-type

N-type means the more accurate the better. Manufacturer A sets the delivery target times for B's trucks to be 6:00AM, 2:00PM, and 10:00PM. If B's trucks arrive later, loss will be caused to A because the production has to slow down or even stop due to out-of-component stock. If B's truck arrives early, it may block the way of other suppliers' trucks or A's trucks out for delivery. The general N-Type hazard function is:

$$H_{MtT-N} = \begin{cases} M^{-} & x < r_2^{-} \\ a^{-}(x-r_1^{-})^2 + c^{-} & r_2^{-} \le x \le r_1^{-} \\ 0 & r_1^{-} < x < r_1^{+} \\ a^{+}(x-r_1^{+})^2 + c^{+} & r_1^{+} \le x \le r_2^{+} \\ M^{+} & r_2^{+} < x \end{cases}$$

where $a^+$, $a^-$, $c^+$, and $c^-$ are hazard parameters. $M^+$ and $M^-$ are the maximum possible loss in the worse cases. Figure 4.4 shows the general N-type hazard function

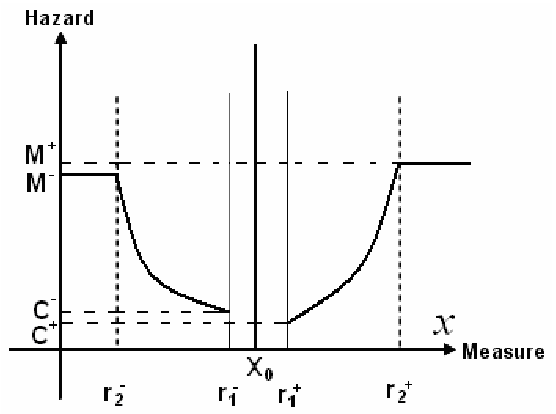


**Figure 4.4 The general N-type hazard function**

### L-type

L-type means the larger the better. Manufacturer A usually orders components from B based on its long-term forecast on sale. Naturally, A sometimes orders more than it actually needs. A expects that B can take 100% responsibility for the extra components it orders. Obviously, B does not want to take the responsibility since it is A that over ordered. However, since A is B’s most important customer, B is willing to take a certain percentage of the responsibility depending on the over-ordered quantity and the orders from other customers. In this case, A expects that B is willing to take 100% of the responsibility. Therefore, the target value is 100%. B may take a certain percentage but never exceeds 100%. If B takes 100%, there is no hazard to A. The less B takes, the worse will be the impact on A. The general L-Type hazard function is:

$$H_{MtT-L} = \begin{cases} M^- & x < r_2^- \\ a^-(x - r_1^-)^2 + c^- & r_2^- \le x \le r_1^- \\ 0 & r_1^- < x \end{cases}$$

where $a^-$ and $c^-$ are hazard parameters, and $M^-$ is the maximum possible loss in the worse case. Figure 4.5 shows the general L-type hazard function

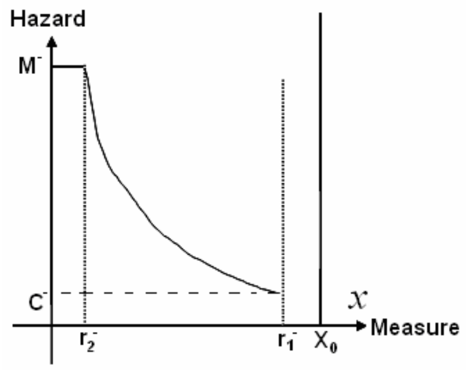


**Figure 4.5 The general L-type hazard function**

Obviously, some buyers may have their hazard functions in different forms. For example, instead of $a^+\Delta x^2 + c^+$, after regression analysis, certain buyers may have their own special functions such as $\sum_i a_i^+\Delta x^i$. However, as long as they follow the general risk function proposed by this chapter, they can still describe and predict MtT-type risks mathematically.

### 4.3.2. MtT-type exposure function

The MtT-type exposure function actually is the frequency function from the historical data and it can be used as the probability function to predict risk in the future. Naturally, firms can use historical data to find their own exposure functions, or use some established and widely adopted distributions. In this chapter, Gamma distribution for S-type exposure function, Beta distribution for L-type exposure function, and Generalized Hyperbolic distribution for N-type exposure function are recommended for their flexibility.

### S-Type

As a general type of statistical distribution, gamma distribution is widely used in the financial industry, especially for credit risk. Since its pdf function has a quite flexible shape, it is recommended for the S-type exposure function. The pdf function for Gamma distribution is:

$$f_{Gamma}(\Delta x;\lambda,\theta)=\frac{\lambda^{\theta}\Delta x^{\theta-1}e^{-\lambda\Delta x}}{(\theta-1)!}=\frac{\lambda^{\theta}\Delta x^{\theta-1}e^{-\lambda\Delta x}}{\Gamma(\theta)}\qquad 0\le\Delta x<\infty$$

where $\Delta x = x - x_0$. The cdf function is:

$$F_{Gamma}(\Delta x;\lambda,\theta)=\int_0^{\Delta x} f_{Gamma}(\Delta x;\lambda,\theta)d\Delta x=\int_0^{\Delta x}\frac{\lambda^{\theta}\Delta x^{\theta-1}e^{-\lambda\Delta x}}{\Gamma(\theta)}d\Delta x$$

It is also called an incomplete Gamma ratio, and it does not have a closed form. However, numerical integration can be used to obtain the value. Figure 4.6 shows the probability density functions for Gamma distributions with different parameters.

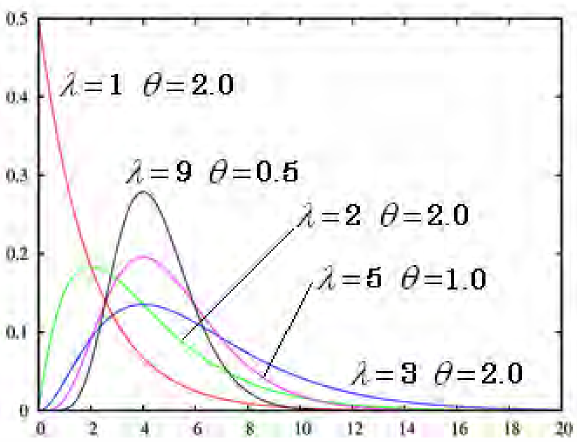


**Figure 4.6 Probability density functions for Gamma distributions**

The mean and variance of Gamma distribution with parameters $\lambda$ and $\theta$ are:

$$\mu=\frac{\theta}{\lambda}\text{ and }\sigma^2=\frac{\theta}{\lambda^2}$$

Since Gamma distribution is a quite common distribution, this chapter will not introduce into detail about how to estimate parameters and how to do the fitness test.

### N-Type

Normal distribution is probably the most commonly used distribution in practice. However, due to it symmetric shape, its application in the financial industry is limited. In a lot of cases, other asymmetric distributions are used such as lognormal. As a much more flexible distribution, generalized hyperbolic distribution is recommended in this chapter for N-type exposure function. Again, firms are free to use any distribution or regression equation as long as it fits their special cases.

Generalized hyperbolic distribution was firstly introduced by Barndorff-Nielsen (1978). Compared to traditional normal distribution with two parameters $\mu$ and $\sigma$, hyperbolic distribution has five parameters $\lambda$, $\alpha$, $\beta$, $\delta$, and $\mu$, and is much more flexible. The density function is:

$$\begin{aligned} f_{GH}(\Delta x;\lambda,\alpha,\beta,\delta,\mu) &= a(\lambda,\alpha,\beta,\delta)(\delta^2+(\Delta x-\mu)^2)^{(\lambda-\frac{1}{2})/2} \\ &\times K_{\lambda-\frac{1}{2}}(\alpha\sqrt{\delta^2+(\Delta x-\mu)^2})\exp(\beta(\Delta x-\mu)) \end{aligned}$$

where $\Delta x = x - x_0$ and $a(\lambda,\alpha,\beta,\delta) = \dfrac{(\alpha^2-\beta^2)^{\lambda/2}}{\sqrt{2\pi}\alpha^{\lambda-\frac{1}{2}}\delta^{\lambda}K_{\lambda}(\delta\sqrt{\alpha^2-\beta^2})}$

is a normalized constant. The values that parameters can take are:

$$\begin{aligned} &\delta \ge 0, \quad |\beta| < \alpha, \qquad if \quad \lambda > 0 \\ &\delta > 0, \quad |\beta| < \alpha, \qquad if \quad \lambda = 0 \\ &\delta > 0, \quad |\beta| \le \alpha, \qquad if \quad \lambda < 0 \end{aligned}$$

$K_v$ denotes the modified Bessel function of the third kind with index $v$. An integral representation of $K_v$ is

$$K_v(z) = \frac{1}{2}\int_0^{\infty} y^{v-1}\exp(-\frac{1}{2}z(y+y^{-1}))dy$$

In the density function, $\alpha$ determines the shape, $\beta$ determines the skewness, $\mu$ determines the location, and $\lambda$ determines the heaviness of the tails. $\delta$ is the scaling parameter, which is comparable to $\alpha$ in the normal distribution. If we define $\zeta = \delta\sqrt{\alpha^2-\beta^2}$ and keep other parameters fixed, Figure 4.7 shows that the normal distribution appears as a limiting case if the $\zeta$ increases to infinity.

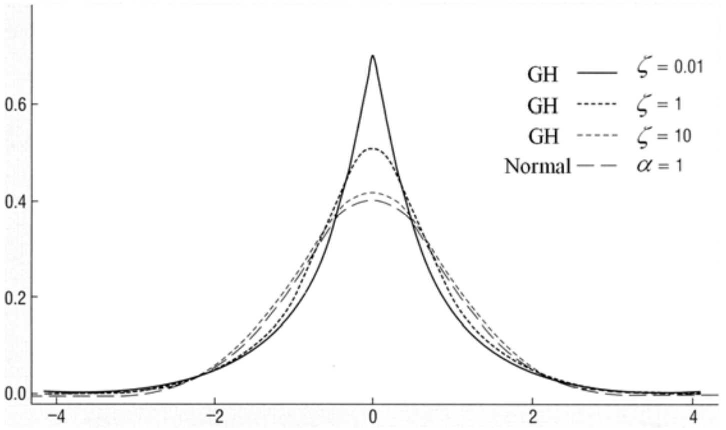


**Figure 4.7 Comparison of Norm distribution with GH distributions**

If we use $\iota^2 = \alpha^2 - \beta^2$, then the mean and the variance of GH distributions are:

$$\mu + \frac{\delta^2 \beta}{\delta\iota} \frac{K_{\lambda+1}(\delta\iota)}{K_\lambda(\delta\iota)} \quad \text{and} \quad \delta^2 \left\{ \frac{K_{\lambda+1}(\delta\iota)}{\delta\iota K_\lambda(\delta\iota)} + \left(\frac{\beta}{\iota}\right)^2 \left[ \frac{K_{\lambda+2}(\delta\iota)}{K_\lambda(\delta\iota)} - \left(\frac{K_{\lambda+1}(\delta\iota)}{K_\lambda(\delta\iota)}\right)^2 \right] \right\}$$

Roughly, about 250 data points are required to fit the generalized hyperbolic distributions. However, about 100 data points can offer reasonable results.

Although maximum-likelihood estimation method can be used to estimate the parameters, it is very difficult to solve such a complicated nonlinear equation system with five equations and five unknown parameters. Therefore, numerical algorithms are suggested, such as a modified Powell method (Wang 2005), in this chapter. Also, the Kolmogorov-Smirnov statistics introduced in section 4.2.1 can be used here for the fitness test.

**L-Type**

Beta distribution is recommended for L-type exposure function. The pdf function is:

$$f_{Beta}(x;\lambda,\theta) = \frac{x^{\lambda-1}(1-x)^{\theta-1}}{\beta(\lambda,\theta)} = \frac{\Gamma(\lambda+\theta)}{\Gamma(\lambda)\Gamma(\theta)} x^{\lambda-1}(1-x)^{\theta-1} \qquad \lambda > 0, \theta > 0$$

where $0 \le x \le 1$. However, the actual $x$ value may not be restricted to range $[0,1]$.

For variable $X$ at any range $[a,b]$, we can do following transformation:

$$Y = \frac{X-a}{b-a}$$

Then, $Y$ follows a beta distribution. The cdf function is:

$$F_{Beta}(y;\lambda,\theta) = \int_0^y f_{Beta}(y;\lambda,\theta)dy = \int_0^y \frac{y^{\lambda-1}(1-y)^{\theta-1}}{\beta(\lambda,\theta)}dy = I_{Beta}(y;\lambda,\theta)$$

where $I_{Beta}(y;\lambda,\theta)$ is called the incomplete Beta ratio, which actually does not have a closed form. However, numerical integration can be used to obtain it. The mean and variance of Beta distribution are:

$$\frac{\lambda}{\lambda+\theta} \text{ and } \frac{\lambda\theta}{(\lambda+\theta)^2(\lambda+\theta+1)}$$

For a random sample, by using the method of moments estimate, the parameter estimators are:

$$\lambda = E(Y)(\frac{E(Y)(1-E(Y))}{\text{var}(Y)} - 1) \text{ and } \theta = (1-E(Y))(\frac{E(Y)(1-E(Y))}{\text{var}(Y)} - 1)$$

Since Beta distribution is a popular distribution, this chapter will not discuss how to do the fitness test.

### 4.3.3. MtT-type risk function

Based on the definition of risk, which is given at the beginning of this chapter, risk has two components: hazard and exposure. Therefore, by aggregating the hazard function from section 4.3.1 and the exposure function from section 4.3.2, the generalized mathematical description of S-type, N-type, and L-type risks can be achieved. $\alpha$ is used in the risk functions to denote quantile. For example, $\alpha = 0.95$ means that in 95% of all cases the loss from certain risk will be less than or equal to the value from the risk functions.

**S-Type risk**

$$R_{MtT-S}(\alpha) = \begin{cases} c^+ & 0 \le \alpha < F_{Gamma}(r_1^+ - X_0; \lambda, \theta) \\ a^+(F_{Gamma}^{-1}(\alpha; \lambda, \theta))^2 + c^+ & \\ & F_{Gamma}(r_1^+ - X_0; \lambda, \theta) \le \alpha \le F_{Gamma}(r_2^+ - X_0; \lambda, \theta) \\ M^+ & F_{Gamma}(r_2^+ - X_0; \lambda, \theta) < \alpha \le 1 \end{cases}$$

where $F_{Gamma}^{-1}(\alpha; \lambda, \theta)$ is the value of $x - X_0$ which makes

$$F_{Gamma}(x - X_0; \lambda, \theta) = \alpha$$

**N-type risk**

Since N-type hazard exists on both sides of the target value, the mathematical description of risk is quite complicated. In total 24 different cases need to be considered depending on the relationship among $M^+$, $M^-$, $C^+$, and $C^-$.

<u>**Case 1:**</u> **If** $M^+ > C^+ \ge M^- > C^-$

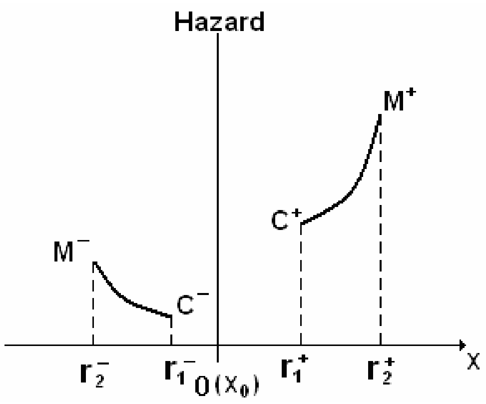


**Figure 4.8 Case 1 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+) - \alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F(r_2^-) \\ M^- & F(r_1^+) - F(r_2^-) \le \alpha < F(r_1^+) \\ a^+(F^{-1}(\alpha))^2 + c^+ & F(r_1^+) \le \alpha \le F(r_2^+) \\ M^+ & F(r_2^+) \le \alpha \le 1 \end{cases}$$

**Case 2: If** $M^+ > M^- > C^+ > C^-$

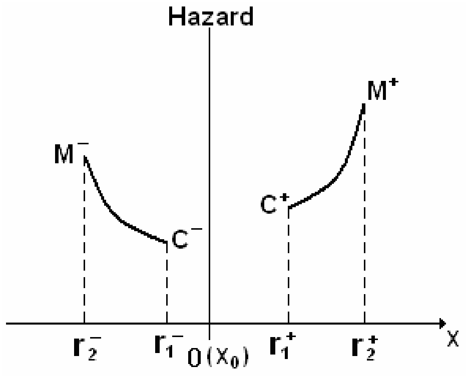


Figure 4.9 Case 2 of N-type risk

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+)-\alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \\ *1 & F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \\ M^- & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \\ a^+(F^{-1}(\alpha))^2 + c^+ & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \le \alpha \le F(r_2^+) \\ M^+ & F(r_2^+) \le \alpha \le 1 \end{cases}$$

$*1$: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le -\sqrt{\dfrac{c^+ - c^-}{a^-}}$ and $r_1^+ \le x'' \le \sqrt{\dfrac{M^- - c^+}{a^+}}$. Then, the risk value is

$$a^-(x')^2 + c^- \quad (\text{or } a^+(x'')^2 + c^+)$$

**Case 3: If** $M^+ > M^- > C^+ = C^-$

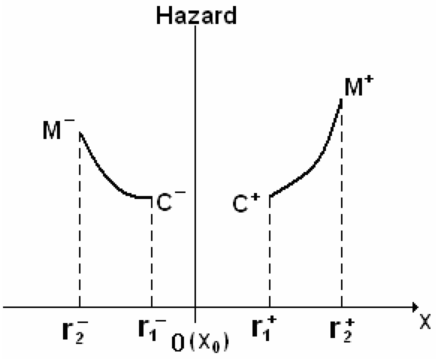


**Figure 4.10 Case 3 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ *1 & F(r_1^+) - F(r_1^-) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \\ M^- & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \\ a^+(F^{-1}(\alpha))^2 + c^+ & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \le \alpha \le F(r_2^+) \\ M^+ & F(r_2^+) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le r_1^-$ and $r_1^+ \le x'' \le \sqrt{\dfrac{M^- - c^+}{a^+}}$. Then, the risk value is

$$a^-(x')^2 + c^- \quad \text{(or } a^+(x'')^2 + c^+ \text{)}$$

**Case 4: If** $M^+ > M^- > C^- > C^+$

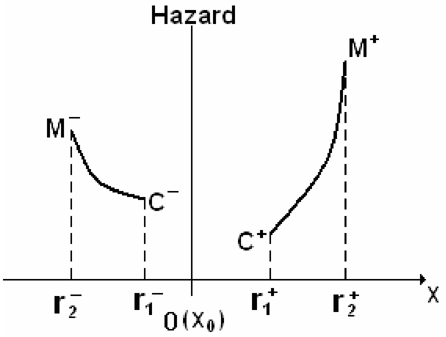


**Figure 4.11 Case 4 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^+(F^{-1}(F(r_1^-)+\alpha))^2 + c^+ & F(r_1^+) - F(r_1^-) \le \alpha \le F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) \\ *1 & F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \\ M^- & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) - F(r_2^-) \le \alpha \le F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \\ a^+(F^{-1}(\alpha))^2 + c^+ & F\left(\sqrt{\dfrac{M^- - c^+}{a^+}}\right) \le \alpha \le F(r_2^+) \\ M^+ & F(r_2^+) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le r_1^-$ and $\sqrt{\dfrac{c^- - c^+}{a^+}} \le x'' \le \sqrt{\dfrac{M^- - c^+}{a^+}}$. Then, the risk value is

$$a^-(x')^2 + c^- \quad (\text{or} \quad a^+(x'')^2 + c^+)$$

**Case 5: If** $M^+ = M^- > C^- > C^+$

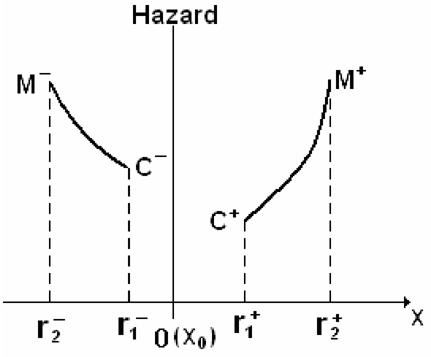


**Figure 4.12 Case 5 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^+(F^{-1}(F(r_1^-)+\alpha))^2 + c^+ & F(r_1^+) - F(r_1^-) \le \alpha \le F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) \\ *1 & F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) - \le \alpha \le F(r_2^+) - F(r_2^-) \\ M^+ & F(r_2^+) - F(r_2^-) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le r_1^-$ and $\sqrt{\dfrac{c^- - c^+}{a^+}} \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad (\text{or } a^+(x'')^2 + c^+)$$

**Case 6: If** $M^+ = M^- > C^+ > C^-$

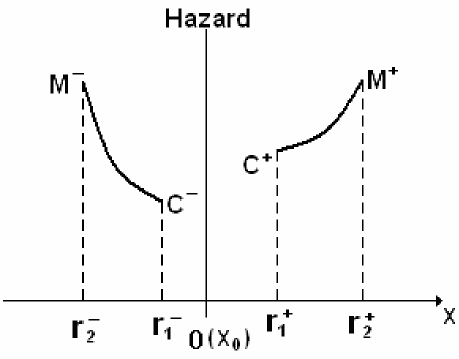


**Figure 4.13 Case 6 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+)-\alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \\ *1 & F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \le \alpha \le F(r_2^+) - F(r_2^-) \\ M^+ & F(r_2^+) - F(r_2^-) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le -\sqrt{\dfrac{c^+ - c^-}{a^-}}$ and $r_1^+ \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad (\text{or } a^+(x'')^2 + c^+)$$

**Case 7: If** $M^+ = M^- > C^- = C^+$

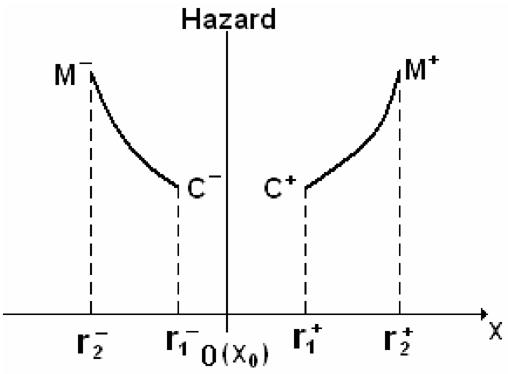


**Figure 4.14 Case 7 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ *1 & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_2^+) - F(r_2^-) \\ M^+ & F(r_2^+) - F(r_2^-) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $r_2^- \le x' \le r_1^-$ and $r_1^+ \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad (\text{or } a^+(x'')^2 + c^+)$$

**Case 8: If** $M^- > C^- \ge M^+ > C^+$

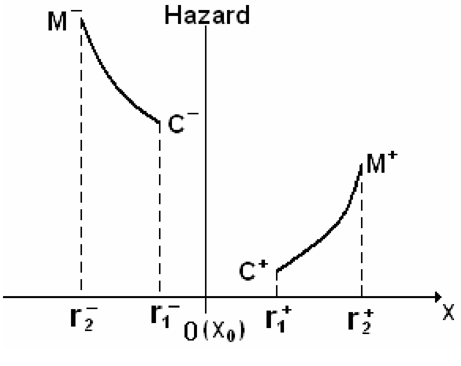


**Figure 4.15 Case 8 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^+(F^{-1}(F(r_1^-) + \alpha))^2 + c^+ & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_2^+) - F(r_1^-) \\ M^+ & F(r_2^+) - F(r_1^-) \le \alpha < 1 - F(r_1^-) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F(r_1^-) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

**Case 9: If** $M^- > M^+ > C^- > C^+$

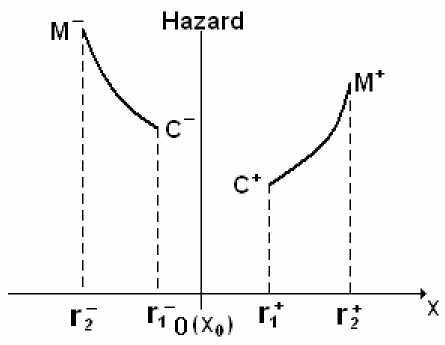


**Figure 4.16 Case 9 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^+(F^{-1}(F(r_1^-)+\alpha))^2 + c^+ & F(r_1^+) - F(r_1^-) \le \alpha \le F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) \\ *1 & F\left(\sqrt{\dfrac{c^- - c^+}{a^+}}\right) - F(r_1^-) \le \alpha \le F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ M^+ & F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

$*1$: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $-\sqrt{\dfrac{M^+ - c^-}{a^-}} \le x' \le r_1^-$ and $\sqrt{\dfrac{c^- - c^+}{a^+}} \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad \text{(or } a^+(x'')^2 + c^+\text{)}$$

**Case 10: If** $M^- > M^+ > C^- = C^+$

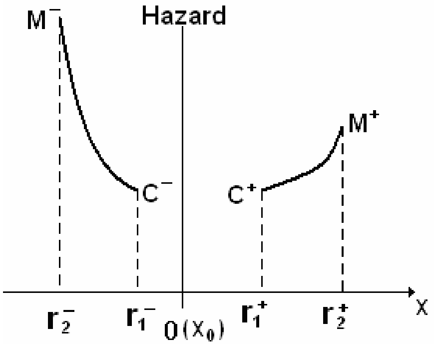


**Figure 4.17 Case 10 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ *1 & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ M^+ & F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

$*1$: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $-\sqrt{\dfrac{M^+ - c^-}{a^-}} \le x' \le r_1^-$ and $r_1^+ \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad \text{(or } a^+(x'')^2 + c^+\text{)}$$

**Case 11:** **If** $M^- > M^+ > C^+ > C^-$

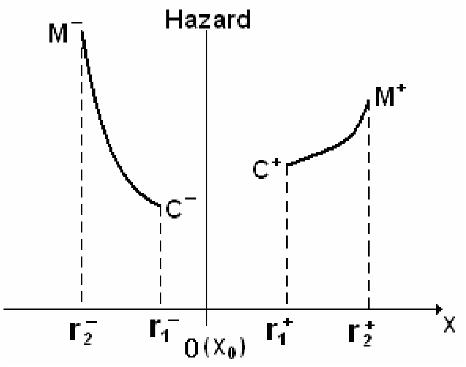


Figure 4.18 Case 11 of N-type risk

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+)-\alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \\ *1 & F(r_1^+) - F\left(-\sqrt{\dfrac{c^+ - c^-}{a^-}}\right) \le \alpha \le F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ M^+ & F(r_2^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

*1: Assume that $x'$ and $x''$ are the solutions to following equations,

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

where $-\sqrt{\dfrac{c^+ - c^-}{a^-}} \le x' \le -\sqrt{\dfrac{M^+ - c^-}{a^-}}$ and $r_1^+ \le x'' \le r_2^+$. Then, the risk value is

$$a^-(x')^2 + c^- \quad \text{(or } a^+(x'')^2 + c^+\text{)}$$

There are also following 13 special cases:

**Case 12: If** $M^- > C^- > M^+$

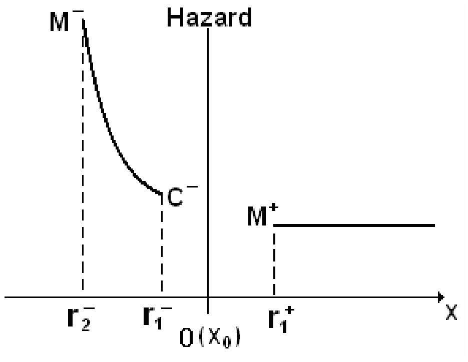


**Figure 4.19 Case 12 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ M^+ & F(r_1^+) - F(r_1^-) \le \alpha < 1 - F(r_1^-) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F(r_1^-) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

**Case 13: If** $M^- > C^- = M^+$

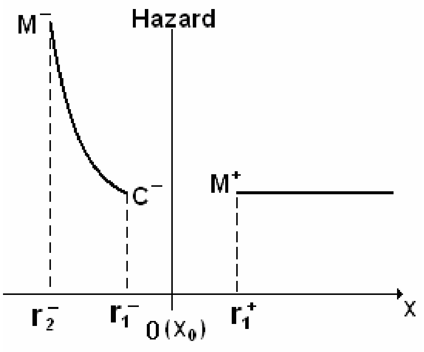


**Figure 4.20 Case 13 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

**Case 14:** **If** $M^- > M^+ > C^-$

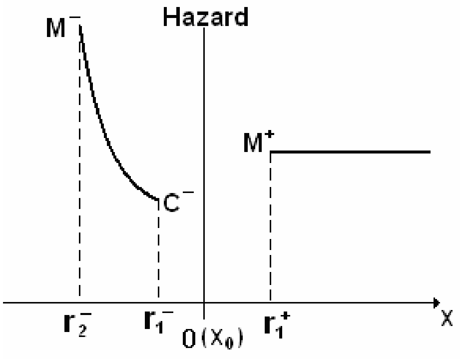


**Figure 4.21 Case 14 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+) - \alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ M^+ & F(r_1^+) - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \\ a^-(F^{-1}(1-\alpha))^2 + c^- & 1 - F\left(-\sqrt{\dfrac{M^+ - c^-}{a^-}}\right) \le \alpha \le 1 - F(r_2^-) \\ M^- & 1 - F(r_2^-) \le \alpha \le 1 \end{cases}$$

**Case 15:** **If** $M^- = M^+ > C^-$

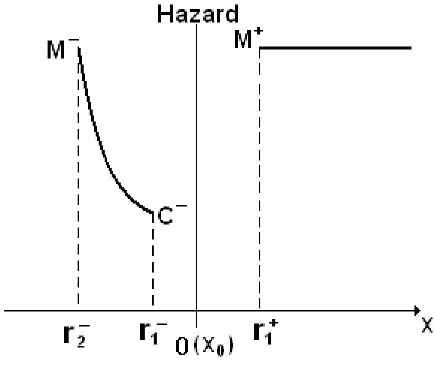


**Figure 4.22 Case 15 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ a^-(F^{-1}(F(r_1^+) - \alpha))^2 + c^- & F(r_1^+) - F(r_1^-) \le \alpha \le F(r_1^+) - F(r_2^-) \\ M^- & F(r_1^+) - F(r_2^-) \le \alpha \le 1 \end{cases}$$

**<u>Case 16:</u> If** $M^{+} > M^{-} > C^{-}$

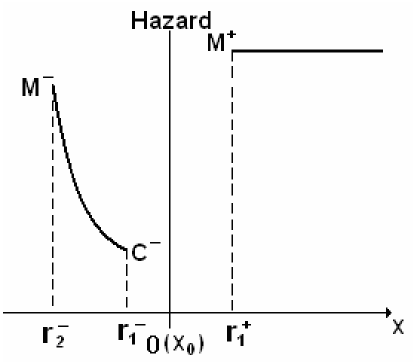


Figure 4.23 Case 16 of N-type risk

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^{+}) - F(r_1^{-}) \\ a^{-}(F^{-1}(F(r_1^{+}) - \alpha))^2 + c^{-} & F(r_1^{+}) - F(r_1^{-}) \le \alpha < F(r_1^{+}) - F(r_2^{-}) \\ M^{-} & F(r_1^{+}) - F(r_2^{-}) \le \alpha < 1 - F(r_1^{+}) \\ M^{+} & 1 - F(r_1^{+}) \le \alpha \le 1 \end{cases}$$

**<u>Case 17:</u> If** $M^{-} > M^{+} > C^{+}$

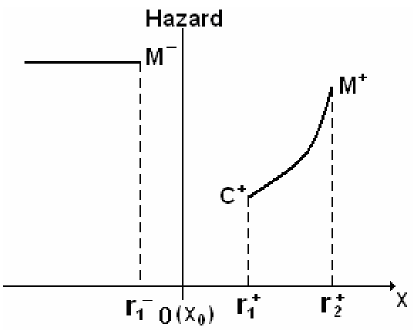


Figure 4.24 Case 17 of N-type risk

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^{+}) - F(r_1^{-}) \\ a^{+}(F^{-1}(F(r_1^{-}) + \alpha))^2 + c^{+} & F(r_1^{+}) - F(r_1^{-}) \le \alpha \le F(r_2^{+}) - F(r_1^{-}) \\ M^{+} & F(r_2^{+}) - F(r_1^{-}) \le \alpha < 1 - F(r_1^{-}) \\ M^{-} & 1 - F(r_1^{-}) \le \alpha \le 1 \end{cases}$$

**<u>Case 18:</u> If** $M^{-} = M^{+} > C^{+}$

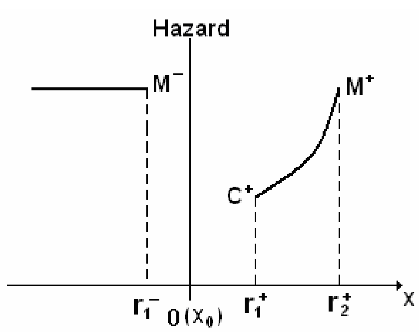


Figure 4.25 Case 18 of N-type risk

$$R(\alpha)_{MtT-N}=\begin{cases}0 & 0\le\alpha<F(r_1^+)-F(r_1^-)\\ a^+(F^{-1}(F(r_1^-)+\alpha))^2+c^+ & F(r_1^+)-F(r_1^-)\le\alpha\le F(r_2^+)-F(r_1^-)\\ M^- & F(r_2^+)-F(r_1^-)\le\alpha\le 1\end{cases}$$

**Case 19: If** $M^+>M^->C^+$

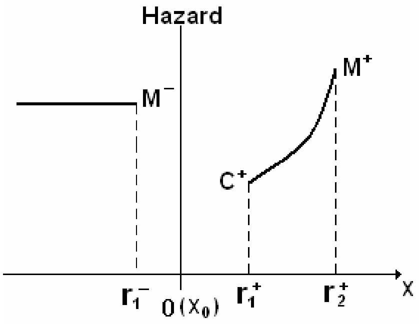


**Figure 4.26 Case 19 of N-type risk**

$$R(\alpha)_{MtT-N}=\begin{cases}0 & 0\le\alpha<F(r_1^+)-F(r_1^-)\\ a^+(F^{-1}(F(r_1^-)+\alpha))^2+c^+ & F(r_1^+)-F(r_1^-)\le\alpha\le F\left(\sqrt{\dfrac{M^--c^+}{a^+}}\right)-F(r_1^-)\\ M^- & F\left(\sqrt{\dfrac{M^--c^+}{a^+}}\right)-F(r_1^-)\le\alpha\le F\left(\sqrt{\dfrac{M^--c^+}{a^+}}\right)\\ a^+(F^{-1}(\alpha))^2+c^+ & F\left(\sqrt{\dfrac{M^--c^+}{a^+}}\right)\le\alpha\le F(r_2^+)\\ M^+ & F(r_2^+)\le\alpha\le 1\end{cases}$$

**Case 20: If** $M^+>M^-=C^+$

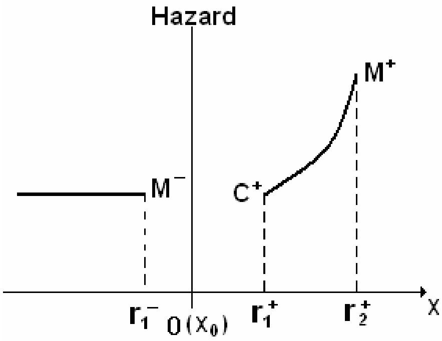


**Figure 4.27 Case 20 of N-type risk**

$$R(\alpha)_{MtT-N}=\begin{cases}0 & 0\le\alpha<F(r_1^+)-F(r_1^-)\\ c^+ & F(r_1^+)-F(r_1^-)\le\alpha\le F(r_1^+)\\ a^+(F^{-1}(\alpha))^2+c^+ & F(r_1^+)\le\alpha\le F(r_2^+)\\ M^+ & F(r_2^+)\le\alpha\le 1\end{cases}$$

**Case 21:** **If** $M^+ > C^+ > M^-$

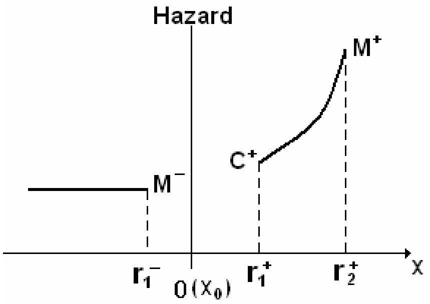


**Figure 4.28 Case 21 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ M^- & F(r_1^+) - F(r_1^-) \le \alpha < F(r_1^+) \\ a^+(F^{-1}(\alpha))^2 + c^+ & F(r_1^+) \le \alpha \le F(r_2^+) \\ M^+ & F(r_2^+) \le \alpha \le 1 \end{cases}$$

**Case 22:** **If** $M^- > M^+$

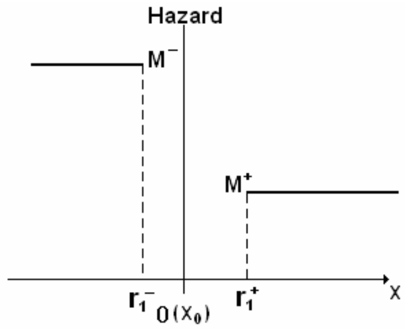


**Figure 4.29 Case 22 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ M^+ & F(r_1^+) - F(r_1^-) \le \alpha < 1 - F(r_1^-) \\ M^- & 1 - F(r_1^-) \le \alpha \le 1 \end{cases}$$

**Case 23:** **If** $M^+ = M^-$

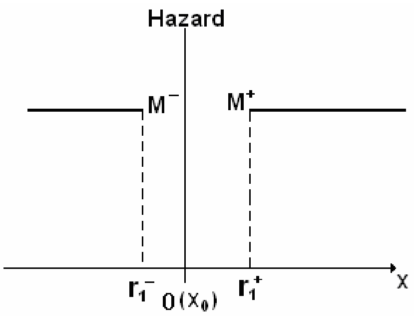


**Figure 4.30 Case 23 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ M^+ & F(r_1^+) - F(r_1^-) \le \alpha \le 1 \end{cases}$$

**Case 24:** **If** $M^+ > M^-$

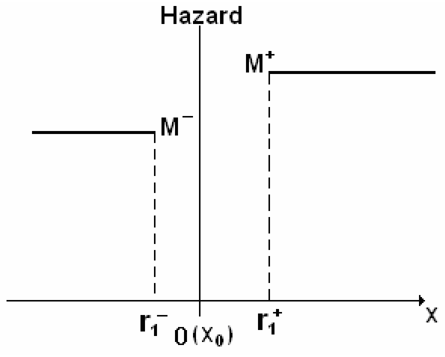


**Figure 4.31 Case 24 of N-type risk**

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < F(r_1^+) - F(r_1^-) \\ M^- & F(r_1^+) - F(r_1^-) \le \alpha < 1 - F(r_1^+) \\ M^+ & 1 - F(r_1^+) \le \alpha \le 1 \end{cases}$$

In order to solve following equations to get $x'$ or $x''$, numerical searching methods may need to be used if $F^{-1}(x)$ can not be expressed in a closed form.

$$\begin{cases} F(x'') - F(x') = \alpha \\ a^-(x')^2 + c^- = a^+(x'')^2 + c^+ \end{cases}$$

**L-Type risk**

Suppose that the possible value range for $x$ is [a, b], then, let

$$y = \frac{x-a}{b-a}$$

Obviously, for L-type risk, $x_0 = b$ and correspondingly, $y_0 = 1$. The L-type risk function is:

$$R_{MtT-L}(\alpha) = \begin{cases} 0 & 0 \le \alpha < 1 - F_{Beta}(\frac{r_1^- - a}{b-a}; \lambda, \theta) \\ a^-(b-a)^2(1 - F_{Beta}^{-1}(1-\alpha; \lambda, \theta))^2 + c^- & \\ & 1 - F_{Beta}(\frac{r_1^- - a}{b-a}; \lambda, \theta) \le \alpha \le 1 - F_{Beta}(\frac{r_2^- - a}{b-a}; \lambda, \theta) \\ M^- & 1 - F_{Beta}(\frac{r_2^- - a}{b-a}; \lambda, \theta) < \alpha \le 1 \end{cases}$$

where $F_{Beta}^{-1}(1-\alpha; \lambda, \theta)$ is the value of $\frac{x-a}{b-a}$ which makes

$$F_{Beta}(\frac{x-a}{b-a}; \lambda, \theta) = 1 - \alpha$$

**Example 4.2**

Computer manufacturer A in the US wants to evaluate the risks from its supplier B in Southern China. Inaccurate delivery time is one of the major problems bothering A due to the long distance. After analyzing the historical data, A found that B's delivery time fits into a generalized hyperbolic distribution with parameters:

$$\lambda = -0.5 \quad \alpha = \beta = 0 \quad \delta = 1 \quad \mu = 0.1$$

This is a special case of generalized hyperbolic distribution called the Cauchy distribution. Then, we can get the pdf function as:

$$f(x) = \frac{1}{\delta\pi(1+((x-\mu)/\delta)^2)} = \frac{1}{\pi(1+(x-0.1)^2)}$$

and cdf function as

$$F(x) = 0.5 + \frac{1}{\pi}\tan^{-1}(x-0.1)$$

After data analysis, A's N-type hazard function is as follows (target value is 0):

$$H_{MtT-N} = \begin{cases} 0 & -0.05 \le x \le 0.05 \\ 4000x^2 + 5000 & 0.05 < x < 2 \\ 1000x^2 + 500 & -2 < x < -0.05 \\ 4,500 & x < -2 \\ 21,000 & x > 2 \end{cases}$$

The above parameters of the hazard function fits into case 1. Then, the MtT-type risk function is

$$R(\alpha)_{MtT-N} = \begin{cases} 0 & 0 \le \alpha < 3.15\% \\ 1000(\tan(-\alpha - 0.015902)\pi + 0.1)^2 + 500 & 3.15\% \le \alpha \le 34.26\% \\ 4500 & 34.26\% \le \alpha < 48.41\% \\ 4000(\tan(\alpha - 0.5)\pi + 0.1)^2 + 5000 & 48.41\% \le \alpha \le 84.58\% \\ 21000 & 84.58\% \le \alpha \le 100\% \end{cases}$$

where $\alpha$ stands for the quantile. For example, if A chooses $\alpha = 0.80$, the above MtT type risk shows that in 80% the cases, the loss will not be larger than \$9,595. The expected value is $\int_0^1 R(\alpha)_{MtT} - N d\alpha$. In this example, the value can be achieved by directly doing integral. However, in other more complicated cases, numerical methods may be necessary instead. By using Excel, the expected value is roughly $7,445.

### 4.4. Risk measures

The reason for quantifying supply risks is to support decision-making regarding the firm’s suppliers. Naturally, the next step is to develop appropriate supply risk measures. Then they can be integrated into various decision-making procedures or models. In this section, a couple of supply risk measures are suggested. Obviously, besides adopting these suggested measures, firms can also develop their own risk measures for different cases.

- **R(α)**: Risk at confidence level α

  R(α) stands for the maximum risk at confidence level α. In other words, it means that in $\alpha \times 100\%$ cases, the risk value will not be larger than R(α).

- **PLe(R)**: The possibility of risk value less than R

  PLe(R) stands for the probability corresponding to risk value R. More specifically, PLe(R) means that the probability of the actual risk value no larger than R is PLe(R). Naturally, $0 \le \text{PLe(R)} \le 1$.

- **PLa (R)**: The possibility of risk value larger than R

  PLa(R) stands for the probability that the actual risk value is larger than R. Naturally, $0 \le \text{PLa(R)} \le 1$ and PLe(R) + PLa(R) = 1.

- **E**: The expected loss from a certain risk

The above measures can be used for both VaR-type and MtT-type risks. R(a), PLe(R), and PLA(R) can be directly found in the risk table for VaR-type risks or the risk function for MtT-type risks. When the risk table does not have the desired value, the linear interpolation method can be used to estimate the real value. Numerical searching methods can be used to find the corresponding $\alpha$ value for a certain risk value from the MtT-type risk functions. In order to get E, an extra calculation needs to be done based on the VaR-type risk table or the MtT-type risk function.

### 4.5. Combining risks

Usually, buyers are facing multiple VaR-type risks and MtT-type risks from the same supplier at the same time. Therefore, different VaR-type risks and MtT-type risks need to be considered together in order to support decision-making. If they have more than one supplier, buyers also need to evaluate the risks from different suppliers as a whole unit. Therefore, there are 3 types of risk combining that need to be done when necessary: combining different VaR-type or MtT-type risks from same supplier, combining same VaR-type or MtT-type risks from different suppliers, and combining of total VaR-type or MtT-type risks from different suppliers. $R_{VaR}(\alpha)$ and $R_{MtT}(\alpha)$ are used in this section to show how to combine different risks. Firms can use the same idea to combine other risk measures.

#### 4.5.1. Combining different VaR-type or MtT-type risks from the same supplier

#### Combining VaR-type risks

This type of combining is fairly easy. It is just the sum of all VaR-type risks based on the same time period assuming that different VaR-type risks are not correlated. For example, if an earthquake caused a fire, and then the fire destroyed a supplier’s manufacturing facility, we consider this risk is from earthquake, not from the fire. In other words, we categorize VaR-type risks by their fundamental sources.

$$R_{VaR}(\alpha;S_i)=\sum_{k=1}^{K}R_{VaR}(\alpha;S_i)_k$$

where

| | |
|---|---|
| $R_{VaR}(\alpha;S_i)_k$ | Suppler $S_i$’s $k$ th VaR-type risk value at quantile $\alpha$ |
| $R_{VaR}(\alpha;S_i)$ | Total VaR-type risk value from supplier $S_i$ at quantile $\alpha$ |

$k$ Index of VaR-type risks, $k = 1, \dots, K$ .

### Combining MtT-type risks

Different MtT-type risks from same supplier are usually not independent. For example, suppose that $R_{MtT}(\alpha; S_i)_1$ is caused by defective components, $R_{MtT}(\alpha; S_i)_2$ is caused by late delivery. Then, if both are considered, the total $R_{MtT}(\alpha; S_i)$ value most likely will not be exactly the sum of $R_{MtT}(\alpha; S_i)_1$ and $R_{MtT}(\alpha; S_i)_2$ , and in most cases, it actually is smaller. For example, both defective components and late delivery can slow down or even stop production. If production was already slowed down or stopped due to late delivery, defective components cannot cause the same level of loss as they originally would have if everything else remains the same because the production has already been impacted. Since too many parameters are involved, it is very difficult to find the exact correlations among different MtT-type risks. In this section, an approximation method is introduced to estimate the final result in order to support decision-making.

Suppose that there are totally $J$ different kinds of MtT-type risks from supplier $S_i$ that need to be combined, and the risk values are $R_{MtT}(\alpha; S_i)_j$ $j = 1, \dots, J$ at quantile $\alpha$ . For each MtT-type risk, suppose $M_j$ is the maximum possible hazard regarding risk $j$ . That is, for L-type risks, $M_j = M_j^-$ ; for S-type risks, $M_j = M_j^+$ ; for N-type, $M_j = \max(M_j^-, M_j^+)$ . Assume $M_{total}$ is the maximum possible hazard in the overall worst case, which means every single measure reaches the worst possible point. Then, the combined $R_{MtT}(\alpha; S_i)$ is

$$M^* = \sum_{j=1}^{J} M_j$$

$$R_{MtT}(\alpha) = \sum_{j=1}^{J} \left( R_{MtT}(\alpha; S_i)_j \times \frac{M_{total}}{M^*} \right)$$

**Example 4.3**

Company A is concerned about 5 different MtT-type risks from its supplier, company B. The first and second are L-type risks and the corresponding $M^-$s are \$540,000 and \$390,000. The third and fourth are S-type risks and the corresponding $M^+$s are \$760,000 and \$560,000. The last one is N-type risks and the maximum possible loss is \$1,200,000. In the worst case, which means when everything with B goes wrong, the overall maximum possible loss to A caused by B is \$2,500,000. A wants to know the total possible loss at a 95% quantile. At first, A calculates the risk value for each MtT-type risk by setting $\alpha = 0.95$. A gets \$510,000, \$350,000, \$710,000, \$480,000, and \$1,000,000. Then, by following the above formula, A can get the combined result.

$$\begin{aligned} M^* &= \$540,000 + \$390,000 + \$760,000 + \$560,000 + \$1,200,000 \\ &= \$3,450,000 \end{aligned}$$

$$\frac{M_{total}}{M^*} = \frac{\$2,500,000}{\$3,450,000} = 0.725$$

$$\begin{aligned} R_{MtT}(95\%) &= (\$510{,}000{+}\$350{,}000{+}\$710{,}000{+}\$480{,}000{+}\$1{,}000{,}000) \times 0.725 \\ &= \$2,211,250 \end{aligned}$$

This means that in 95% of all cases, the loss will not be larger than \$2,211,250.

### 4.5.2. Combining same VaR-type or MtT-type risks from different suppliers

#### Combining VaR-type risks

It is the sum of $k$ th VaR-type risk values from all suppliers

$$R_{VaR}(\alpha; S)_k = \sum_{i=1}^{I} R_{VaR}(\alpha; S_i)_k$$

| where | | |
|---|---|---|
| where | $R_{VaR}(\alpha; S)_k$ | Supply base's total risk value regarding VaR-type risk $k$ at confidence level $\alpha$ |
| | $R_{VaR}(\alpha; S_i)_k$ | Supplier $i$'s VaR-type risk value at confidence level $\alpha$ regarding VaR-type risk $k$ |

**Combining MtT-type risks**

Since it is reasonable to assume that there is no correlation among the same MtT-type risk from different suppliers because MtT-type risks are mainly decided by internal operations, the combining result is just the sum of the risks from different suppliers.

$$R_{MtT}(\alpha;S)_j = \sum_{i=1}^{I} R_{MtT}(\alpha;S_i)_j$$

where $R_{MtT}(\alpha;S)_j$ Supply base's risk value regarding MtT-type risk $j$

$R_{MtT}(\alpha;S_i)_j$ Risk value from supplier $S_i$ regarding MtT-type risk $j$

### 4.5.3. Combining total VaR-type or MtT-type risks from different suppliers

**Combining VaR-type risks**

The total VaR-type risk from a buyer's supply base is just the sum of the VaR-type risks from all suppliers.

$$R_{VaR}(\alpha;S) = \sum_{i=1}^{I} R_{VaR}(\alpha;S_i)$$

**Combining MtT-type risks**

The overall MtT-type risk from a buyer's supply base is the sum of the MtT-type risks from all suppliers.

$$R_{VaR}(\alpha;S) = \sum_{i=1}^{I} R_{MtT}(\alpha;S_i)$$

### 4.5.4. Considering suppliers' weights in the supply portfolio

The above combining methods can be used for buyers to evaluate their current supply base. In this case, the suppliers' weights in the supply portfolio are known and fixed. A supplier's weight to the buyer is defined here as the ratio of the total contracts' value with this supplier to the overall value of all the contracts with all the suppliers. For example, if buyer A plans to spend \$50 million for all the component and material purchases in the coming fiscal year, and A plans to buy \$10 million worth of components from supplier B, then, B's overall weight in the supply portfolio of A is 0.20. More specifically, \$1 million will be used to purchase component D, and B will supply 50% of D to A. Then, regarding component D, B's weight is 0.5 although its overall weight is 0.2. This shows that suppliers' weights regarding different material and component categories or items may be different. Naturally, when a supplier's weights change, the risks from this supplier also change. In other words, risks are also functions of supplier's weights. The risk from a supplier with weight 0.9 is definitely different than if this supplier's weight is 0.7. In cases where buyers need to evaluate risks when weights are changing such as adjusting the current supply base by bring in new suppliers to replace old ones, in order to avoid too much work for data collection, simulation, etc. to get the accurate risk values for every possible new weight, approximation can be done to come up with rough estimates. Following are the possible approximation methods for different cases.

**Method 1**:

Suppose that company B is company A's supplier and its weight to A currently is $W_B$. The VaR-type risk values from B are $R_{VaR}(\alpha;B)_k$ and the MtT-type risk values from B to A are $R_{MtT}(\alpha;B)_j$. If A wants to change B's weight to $W_B^*$, the new risk values can be estimated by $R_{VaR}(\alpha;B)_k \times \frac{W_B^*}{W_B}$ and $R_{MtT}(\alpha;B)_j \times \frac{W_B^*}{W_B}$. $W_B$ and $W_B^*$ could be the overall weights or the weights regarding a category or even a special component. The basic idea is the same.

**Method 2**:

Suppose that currently B is not in A's supply base but A is considering having B included. A can collect all the required data and may run some simulations to figure out $R_{VaR}(\alpha;B)_k$ and $R_{MtT}(\alpha;B)_j$ pretending B is the only supplier. Then, for any given weight $W_B$, $R_{VaR}(\alpha;B)_k \times W_B$ and $R_{MtT}(\alpha;B)_j \times W_B$ can be used to estimate the corresponding risk values.

**Method 3**:

Since risk values may not have exact linear relationships with weights, buyers can achieve better estimation results by getting more data points for interpolation. For example, A can set $W_B$ to 0.2, 0.4, 0.6, 0.8, and 1.0 and then figure out all the corresponding risk values. Then, risk values corresponding to new weights can be estimated by interpolation using the nearby two data points. If the new weight is 0.35, 0.2 and 0.4 will be used. The more data points A prepares, the more accurate the estimates will be. Method 2 actually is also an interpolation method with only two points, $W_B = 0$ and $W_B = 1.0$. Method 1 is the same. If enough data points are available, A can even find the regression models for the risk values using weights as independent variables, and thus better results can be achieved.

### 4.6. How to use external data

In this section, the use of external similar data for quantitative risk management is introduced.

#### 4.6.1. External historical data are available

For example, manufacturer A is considering having company B as its long-term supplier. Naturally, A wants to evaluate the risks. Since A never did business with B before, A does not have any data available. However, A managed to get some data from firms C, D, and E. All of them had business with B before. Therefore, A can try to use the data from C, D, and E to estimate the risks from B. Although people can argue the feasibility of this “data-borrowing”, this is much better than making guesses.

Suppose that the buyer has data available from $N$ sources, with source $j$

having sample size $n_j$ and observation data $D_{i,j}$, $i = 1, 2, ..., n_j$. If we assume $D_j(Q)$ to be the quintile function of the frequency distribution at source $j$, $0 < Q < 1$. Then,

$$D_j(Q) = \phi_j d(Q) \qquad j = 1, ..., n$$

where $\phi_j$ is the similarity less index (SLI). $\phi_j$ can be estimated by $\overline{D}_j$, which is the sample average at source $j$. Then, data can be rescaled as:

$$d_{i,j} = \frac{D_{i,j}}{\widehat{\phi_j}} \qquad j = 1, ..., N; \quad i = 1, ...n_j,$$

Then, $d_{i,j}$ can be used as the basis for regression analysis.

### 4.6.2. External distributions are available

Suppose that manufacturer A in the above example managed to get the distributions of B’s performance from its other customers, A can use those distribution directly to estimate B’s performance in the future if those distributions have the same form, although the parameters’ values are different.

Assume that the form of distribution $d(Q)$ is known, and $d(Q)$ has $p$ parameters, $\theta^1, \theta^2, ..., \theta^P$. Therefore, we can also write $d(Q)$ as $d(Q; \theta^1, \theta^2, ..., \theta^P)$. Suppose that A has distribution information available from $N$ sources, with source $j$ having sample size $n_j$ and the distribution $d_j(Q; \theta_j^2, \theta_j^3, ..., \theta_j^P)$ in the same form. Then, following formula can be used to estimate the parameters $\theta^1, \theta^2, ..., \theta^P$.

$$\widehat{\theta^k} = \frac{\sum_{j=1}^{N} n_j \theta_j^k}{\sum_{j=1}^{N} n_j} \qquad \forall k = 1, 2, ..., P$$

# Chapter 5

# Supplier Selection at Strategic Level Considering Risk

Supplier selection at the strategic level is one of the most important decisions that a firm needs to make. It is also one of the most difficult because a lot of tangible and intangible factors need to be considered including design capabilities, production capacities, business strategy, and financial status. Buyers are always looking for the suppliers who can offer the lowest price, highest quality, most advanced design, on-time delivery, etc. However, such suppliers may not exist since it is really hard to be better than competitors in every aspect. Therefore, in most cases, tradeoffs have to be made. In this chapter, a strategic supplier selection method considering risks is proposed. It has the following five steps:

Step 1. Identify the factors that need to be considered for supplier selection hierarchically and then calculate the weight ranges

Step 2. Collect data including potential suppliers' performance for each criterion and then calculate their ***strategic values***

Step 3. Reduce the candidate list to a desirable length by using the *Fuzzy Weighted Best Ranking* (FWBR) model

Step 4. Use several multi-criteria optimization models to identify the best suppliers

Step 5. Present the list of best suppliers to senior managers who make the final decision

The above five steps are discussed in this chapter, and an example is given at the end to show how this method works.

## 5.1. Hierarchical structure of criteria and their weights (Step 1)

Similar to most supplier selection methods, selection criteria need to be identified as the first step. Since there are numerous papers that discuss this topic, this chapter will not give any details about how to identify criteria and which criteria usually need to be considered. Supply risk measures including the ones developed in Chapter 4 can be used in this 5-step method, and therefore, corresponding data need to be collected as well.

Criteria need to be considered hierarchically. In other words, criteria need to be categorized. For example, one of the main categories of focus is cost, and a lot of detailed cost-related criteria need to be evaluated in this category such as delivery cost, per item cost, per order cost, return charges, etc. Sub-categories may also exist if necessary. Figure 5.1 shows an example.

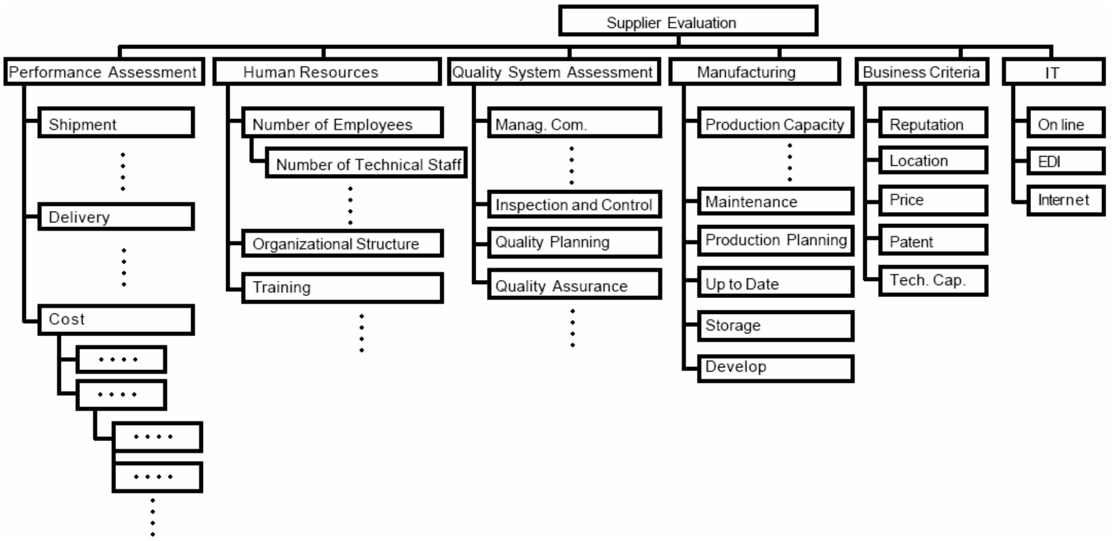


**Figure 5.1 An example of the hierarchical structure of criteria**

Firms may need to consider different criteria with different structures based on their own needs. Therefore, there is no fixed structure for firms to follow. Obviously, the more important the suppliers will be, the more criteria need to be included in the selection process.

Once the hierarchy structure of the criteria has been defined, the weight of each criterion and category can be calculated by using the pair-wise comparison method at each level. In this step, instead of assigning a certain number to a linguistic expression such as 2.5 to “moderate preference”, a range called ***preference range*** is assigned to it. Thus decision makers do not have to face some tough questions such as “Delivery time is a little more important than the unit price, so should we give it 1.7 or 1.8?”

“Why is the number for moderate preference 3 instead of 2.8?” “What is the difference between 2 and 2.5?” “Criteria A and B are about the same. However, A could be a little bit more important than B or B could be a little bit more important than A. So what number should we give to it?” A range instead of a fixed number can solve the dilemma and thereby give decision makers the confidence and the comfort to express their ideas and not worry that a better supplier will not be selected just because they used 1.0 instead 1.3 or 0.8.

This method actually is an extension of the traditional Analytic Hierarchy Process (AHP) method (Zaim et al. 2003). AHP is a mathematical decision-making technique that allows consideration of both qualitative and quantitative aspects of decisions. It reduces complex decisions to a series of pairwise comparisons and then synthesizes the results. Compared to other techniques like ranking or rating techniques, AHP uses the human ability to compare alternatives on a single criterion. It not only helps decision makers choose the best alternative, but also provides a clear rationale for the choice. The process was developed in the 1970s by Thomas Saaty.

In our method, we use a preference range a preference range $(PL, P, PU)$ with three elements: lower bound $PL$, preferred value $P$, and upper bound $PU$, where the preferred value $P$ is the value if the traditional AHP method is used. Obviously, firms can design their own linguistic descriptions for the relationship between different criteria and categories, and then assign appropriate preference ranges to them. Table 5.1 shows an example. Users can modify it to suit their needs.

**Table 5.1 Linguistic descriptions and corresponding preference ranges**

| Linguistic Descriptions | Lower Bound | Preferred | Upper Bound |
|---|---|---|---|
| Equal | 1 | 1 1/2 | 2 |
| Slightly preferred | 1 1/2 | 2 | 2 1/2 |
| Moderately preferred | 2 1/2 | 3 1/2 | 4 1/2 |
| Strongly preferred | 4 1/2 | 5 1/2 | 6 1/2 |
| Very strongly preferred | 5 1/2 | 6 1/2 | 7 1/2 |
| Extremely preferred | 7 1/2 | 8 1/2 | 9 1/2 |

Following are the definitions of the calculations for preference range:

Let $L_i$ be the linguistic descriptions, and the corresponding preference range is $(PL_i, P_i, PU_i)$. Then the following relationships are true:

$$\frac{1}{L_i} = \frac{1}{(PL_i, P_i, PU_i)} = \left(\frac{1}{PU_i}, \frac{1}{P_i}, \frac{1}{PL_i}\right)$$

$$\frac{(PL_i, P_i, PU_i)}{M} = \left(\frac{PL_i}{M}, \frac{P_i}{M}, \frac{PU_i}{M}\right) \quad \text{where M is a constant}$$

$$(PL_i, P_i, PU_i) + M = (PL_i + M, P_i + M, PU_i + M) \quad \text{where M is a constant}$$

$$(PL_i, P_i, PU_i) + (PL_j, P_j, PU_j) = (PL_i + PL_j, P_i + P_j, PU_i + PU_j)$$

$$(PL_i, P_i, PU_i) \times (PL_j, P_j, PU_j) = (PL_i \times PL_j, P_i \times P_j, PU_i \times PU_j)$$

$$\frac{(PL_i, P_i, PU_i)}{(PL_j, P_j, PU_j)} = \left(\frac{PL_i}{P_j}, \frac{P_i}{P_j}, \frac{PU_i}{P_j}\right)$$

Similar to the traditional AHP method, pair-wise comparisons of different criteria and/or categories at the same level need to be done first. The difference in the preference range method is that the non-diagonal entries in the comparison matrix are preference ranges instead of single values. Following AHP calculations, each entry in the matrix (non-diagonal entries are ranges and diagonal entries are 1s) needs to be divided by the sum of the column. Row averages are then calculated. ***Weight ranges***, instead of single weights, are achieved finally for the criteria. An example is given at the end of this chapter to illustrate all the calculations.

### 5.2. Calculating the *strategic values* (Step 2)

After the criteria and their weights are decided, the next step is to collect data. Then a score can be assigned to each candidate supplier for each criterion. A common problem of most methods and applications is that the scores are mainly decided by candidates' past performance. In other words, although some criteria such as long-term development capabilities are considered, buyers are actually using yesterday's data to make the decisions for the future. Superficially, it seems that there is nothing wrong with this since nobody knows those candidates' performance in the future and therefore, making decisions based on their past and current performance is a natural choice. However, this does have problems. For example, suppose that A is a buyer, and A wants to select a strategic supplier for the next 10 years, and the only selection criterion is defective rate. B and C are the candidates. B's current defective rate is 0.5% and C's is 0.7%. Therefore, B should be chosen. However, what might happen later is that C manages to continuously improve its products' quality and after 3 years, its defective rate decreases to 0.3%. B also has a similar quality improvement program but less successful, and its defective rate only drops to 0.4% after 3 years. Then, 3 years later, A will regret its decision of choosing B instead of C. Now the question is how can A know that C actually will be better than B after 3 years? What if C becomes better than B right after 5 years?

Using forecasted data to schedule production, manpower, etc., is quite common in industries. So, why shouldn't buyers do the same to select strategic suppliers? Their performance in the future is what really matters. In this section, a concept called ***strategic value*** is proposed to gauge future performance. The idea is quite similar to stock price valuation, which is supposed to show the total value of each share in the future.

***Strategic Value***: the total value that a supplier can add to the buyer during a certain time period in the future. It is the sum of the discounted performance scores in that period.

$$V_{(i,j)}(0)=\sum_{t=0}^{T-1}S_{(i,j)}(t)=\sum_{t=0}^{T-1}\frac{S_{(i,j)}(0)\times(1+g_{(i,j)})^{t}}{(1+k_j)^{t}}$$

where

| | |
|---|---|
| $V_{(i,j)}(0)$ | Current strategic value of supplier $i$ regarding criterion $j$ to the buyer. |
| $S_{(i,j)}(0)$ | Supplier $i$'s current performance score regarding criterion $j$. The current average of all suppliers with respect to criterion $j$ is set to 1. Therefore, if $i$'s current performance is better than average, then $S_{(i,j)}(0)>1$. If $i$'s current performance is worse than average, then $S_{(i,j)}(0)<1$. If $i$'s current performance is the average, then $S_{(i,j)}(0)=1$. |
| $k_j$ | Estimated changing rate of the average performance score regarding criterion $j$ in the whole industry. $k_j$ usually is greater than 0, which means that the average performance of the whole industry is improving. If $k_j<0$, the average performance of the whole industry is declining. |
| $g_{(i,j)}$ | Estimated changing rate of $i$'s performance score regarding criterion $j$. $g_{(i,j)}$ could be positive or negative. However, in most case, it is positive. |
| $T$ | The contract-ascertained or estimated time period in the future that the buyer will cooperate with supplier $i$. |

$k_j$ and $g_{(i,j)}$ are assumed to be constant or as known functions of time $t$ when calculating the strategic value. $k_j$ and $g_{(i,j)}$ can be updated when buyers update their calculations about strategic values later on.

When selecting suppliers, in order to calculate the strategic values, the "raw" scores of candidates need first to be normalized. Suppose that the raw scores are $S'_{(i,j)}(0)$, where $i=1,...,I$ stands for suppliers and $j=1,...,J$ stands for criteria. Then, the normalized scores $S_{(i,j)}(0)$ can be calculated by

$$S_{(i,j)}(0)=\frac{\text{Supplier i's score regarding criterion j}}{\text{Industry average score regarding criterion j}}$$

Since it may be hard to get the industry average score regarding certain criterion, the average score from candidates can be used as an estimate. Therefore,

$$S_{(i,j)}(0) = \frac{\text{Supplier i's score regarding criterion j}}{\text{Average score of all suppliers regarding criterion j}} = \frac{S'_{(i,j)}(0) \times I}{\sum_{i=1}^{I} S'_{(i,j)}(0)}$$

where $I$ = total number of suppliers

### 5.3. Fussy weighted best ranking method (Step 3)

Firms usually tend to have a long candidate list at the very beginning because they do not want to miss any good ones. All the candidates on the list may satisfy the most basic requirements from the buyer such as ISO 9001, the maximum VaR value, etc. Since supplier evaluation and selection processes cost time and money, the list should be shortened to a manageable length as early as possible by using some relatively simple methods before more complicated steps are used to choose the winner(s). This section introduces a ranking method using weight ranges called Fuzzy Weighted Best Ranking (FWBR) that can help buyers identify the candidates that should be selected from the original list before selecting the winners. The basic idea is to find out the best possible rank that each candidate can achieve. Then, the “hopeless” ones can be eliminated. It should be pointed out here that if the criteria weights are known constants, we can rank the suppliers from the best to worst easily. However, we assume a range for each criterion weight. Thus, the proposed FWBR method determines the best possible ranking for each candidate supplier.

**Index**

| | |
|---|---|
| $i$ | Index of the candidate suppliers in the list, $i = 1, 2, 3......., I$ |
| $j$ | Index of the criteria/categories, $j = 1, 2, 3......., J$ |

**Parameters**

| | |
|---|---|
| $V_{(i,j)}(0)$ | Candidate $i$ ’s current strategic value regarding criterion/category $j$ |
| $WL_j$ | The lower bound of criterion/category $j$ ’s weight |
| $WU_j$ | The upper bound of criterion/category $j$ ’s weight |

| | |
|---|---|
| $s$ | Index of a particular supplier that the buyer wants to find the best possible rank, $1 \le s \le I$ |
| $M$ | An arbitrary large positive number |

**Decision Variables**

| | |
|---|---|
| $W_j$ | The weight of criterion/category $j$ that enables supplier $s$ to achieve the highest possible rank. $WL_j \le W_j \le WU_j$ |
| $V_i$ | The total current strategic value of candidate $i$ with weight set $W_j$ |
| $B_i$ | Binary variable assigned to each supplier |

**Constraints**

- The unknown criteria weights have to fall into the ranges specified:

$$WL_j \le W_j \le WU_j \qquad \forall j$$

- The sum of the weights is 1:

$$\sum_j W_j = 1$$

- The total current strategic value of each supplier equals the sum of the products of the current strategic value for each criterion and the corresponding weight:

$$V_i = \sum_j W_j \times V_{(i,j)}(0) \qquad \forall i$$

- $P_i, N_i$ are introduced here to calculate how many candidates rank higher than candidate $s$ based on strategic value:

$$V_i - V_s = P_i - N_i \qquad \forall i \ \& \ i \ne s$$

$$B_i \times M \ge P_i \qquad \forall i$$

Note: If supplier $i$ has a larger total strategic value than $s$ based on the chosen weights, then $P_i$ has to be greater than 0 since both $P_i$ and $N_i$ are non-negative, and $B_i = 1$. Otherwise, $N_i > 0$ and $B_i = 0$. In other words, if supplier $i$ has higher strategic value than $s$, $B_i = 1$, otherwise, $B_i = 0$.

- Non-negative

$$P_i \geq 0 \qquad \forall i$$
$$N_i \geq 0 \qquad \forall i$$

- Binary

$$B_i = 0 \; or \; 1 \qquad \forall i$$

**Objective Function**

Minimize the total number of suppliers who have higher strategic values than the candidate supplier $s$:

$$\text{Min} \quad Z = \sum_i B_i$$

Then, the best possible rank candidate $s$ can achieve is $Z+1$ since there are Z candidate suppliers who have higher strategic values irrespective of how the criteria weights vary within their ranges.

After running the FWBR model for each candidate from $s=1$ to $s=I$, the buyer can find out that $n_1$ suppliers could rank 1st, $n_2$ suppliers could rank 2nd, etc. Based on how many suppliers that the buyer wants to have in the "shortlist," the corresponding candidates can be selected to enter the next step. For example, if the buyer only wants to consider those ranked first, $n_1$ suppliers would enter the next step. If the buyer wants to consider those ranked in the top 3, $n_1+n_2+n_3$ suppliers enter the next step.

### 5.4. Multi-criteria supplier selection models (Step 4)

Supplier selection basically is a multi-criteria optimization problem. Buyers have many objectives such as low cost, high quality, fast delivery, advanced design, and low risk. Tradeoffs usually have to be made since normally no candidate can be perfect in every single aspect.

There are different approaches (models) to solve the multi-criteria optimization problem such as goal programming, compromise programming, etc. By using different models, a firm may get different best compromised solutions. In many cases, it is hard to tell which model's solution is the best. Therefore, Step 4 in this 5-step method proposes to use different models to solve the multi-criteria optimization problem, and then, in Step 5, the senior managers can make the final decision. In this way, their years of experience and trained intuition can be fully utilized.

Three widely used multi-criteria optimization models are discussed next to fully demonstrate Step 4 of the proposed 5-step method. They are the fuzzy goal programming model, the non-preemptive programming model, and the preemptive goal programming model. Obviously, users are not limited to using these three models. They can use other models based on their past experience or preference. Before developing the common constraints and objective functions of the multi-criteria supplier section problem, the method for calculating the strategic value of supply portfolio (weighted combination of candidates) is introduced.

### 5.4.1. Calculating supply portfolio's strategic value

The supply portfolio's overall performance will be decided by the selected suppliers and their weights. Depending on the type of objective used, the relationship between the overall performance of the supply portfolio and the individual supplier's performance can be different. The three most common objectives are introduced below. Note that strategic values are used in the calculation instead of performance scores.

| | |
|---|---|
| $r_i$ | Supplier $i$'s weight in the supply portfolio, which is defined as the ratio of the contract's value with supplier $i$ to the total value of all the contracts with suppliers. $\sum r_i = 1$ |
| $V_{(i,j)}(0)$ | Supplier $i$'s current strategic value regarding criterion/category $j$ |
| $PV_j(0)$ | Supply portfolio's strategic value regarding criterion/category $j$ |

***Linear combination***

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0)$$

***Minimum***

$$PV_j(0) = \min \left\{ V_{(i,j)}(0) \quad \forall i \right\}$$

***Maximum***

$$PV_j(0) = \max \left\{ V_{(i,j)} \quad \forall i \right\}$$

### 5.4.2. Constraints

Following are the typical constrains that buyers may have when building multi-criteria optimization models.

**Maximum and minimum numbers of suppliers**

One of the major disadvantages of having multiple suppliers is the management difficulties. Usually, the more suppliers a firm has, the more difficult the management will be. Therefore, firms may not want to have more than a certain number of suppliers. Similarly, firms may want to have at least a certain number of suppliers to keep its supply base safer.

$$N_{\min} \le n \le N_{\max}$$

where

| | |
|---|---|
| $n$ | number of the suppliers in the final solution |
| $N_{\max}$ | Maximum number of suppliers that the buyer is willing to have |
| $N_{\min}$ | Minimum number of suppliers that the buyer is willing to have |

**Maximum and minimum weights**

Buyers may have an upper limit and a lower limit for a supplier’s weight in their supplier portfolios. If a certain supplier’s weight is too high, buyers may be concerned about supply risk. If a certain supplier’s weight is too low, buyers may think that it is not worth the trouble to have it in the portfolio.

$$r_{\min} \le r_i \le r_{\max}$$

where

| | |
|---|---|
| $r_i$ | The weight supplier $i$ carries in the portfolio |
| $r_{\max}$ | Upper limit of a supplier's weight in the portfolio |
| $r_{\min}$ | Lower limit of a supplier's weight in the portfolio |

### 5.4.3. Objectives

**Maximize supply portfolio's strategic value**

$$Max \quad \sum_j PV_j(0) \times W_j$$

where

$W_j$ is a decision variable, and $WL_j \le W_j \le WU_j$

We can always assume that higher $PV_j$ value is better for all $j$.

**Minimize supply portfolio's MtT-type risk**

$$Min \quad \sum_i R_{MtT}(\alpha; S_i)$$

The way to combine different type of MtT risks from different suppliers has already been shown in Chapter 4. As discussed in section 4.5.4, the total MtT-type risk value from a supplier depends on its weight $r_i$ in the supply portfolio. Therefore, from now on, $R_{MtT}(\alpha; S_i)$ is expressed as $R_{MtT}(\alpha; r_i)$ where $r_i$ is supplier $S_i$'s weight in the supply portfolio.

**Minimize portfolio's VaR value**

$$Min \quad \sum_i R_{VaR}(\alpha; S_i)$$

Similarly, how to combine different type of VaR risks from different suppliers has already been shown in Chapter 4. Since the total VaR-type risk value from a supplier also depends on its weight in the supply portfolio, from now on, $R_{VaR}(\alpha; S_i)$ is expressed as $R_{VaR}(\alpha; r_i)$ where $r_i$ is supplier $S_i$'s weight in the supply portfolio.

Instead of minimizing or maximizing certain objectives, buyers may have certain goals about performance or risks for the supplier portfolio to reach. In those cases, some objective functions may turn into constrains.

### 5.4.4. Multi-criteria optimization models

Multi-criteria optimization, also known as Multiple Criteria Decision Making (MCDM), Vector Maximum Problem (VMP), or Multiple Criteria Mathematical Programming (MCMP), mainly deals with problems with multiple conflicting criteria (objectives). According to Zeleny (1982), multiple criteria problems have existed for as long as there have been decisions to be made. Similarly, according to Raiffa (1970), Von Von Neuman and Morgenstern (1947) developed the modern probabilistic theory of utility, which is the beginning of multiple criteria analysis. Koopmans (1951) was the first researcher to use the concept of the efficient vector, a solution of modern MCDM. In 1961, Charnes and Cooper published their book on goal programming. Two years later, Bod (1963) presented the "multi-criterion simplex method" to start the line of thinking of linear multi-objective programming. Today, MCDM has been widely used in almost every industry, and there are many papers introducing its application as well as theoretical research.

According to Saaty (1996), there are two parts to the multi-criteria problem: how to measure what is known as intangibles, and how to combine their measurements to produce an overall preference or ranking. Saaty (1996) presents four major approaches or methodologies to solve multi-criteria problems. First is the Analytic Hierarchy Process (AHP), a utility and value theory of economics based on the use of lottery comparisons. The second approach is probabilistic, based on Bayesian Theory. Third is the outranking Method based on ordinal comparison of concordance and discordance. And fourth is the Goal programming that is basically a modified version of Linear Programming (Ignizio 1976).

The supplier section problem in this chapter belongs to the Goal programming category. In this category, the most popular models are preemptive, non-preemptive, Chebyshev, fuzzy, etc. In this section, the fuzzy goal programming model, non-preemptive goal programming model, and preemptive goal programming model for strategic supplier selection are presented.

**Index**

| | |
|---|---|
| $i$ | Number of suppliers in the list $i = 1, 2, 3......., I$ |
| $j$ | Number of criteria/categories $j = 1, 2, 3......., J$ |
| $k$ | Number of VaR risk types $k = 1, 2, 3......., K$ |

**Parameters**

| | |
|---|---|
| $V_{(i,j)}(0)$ | Supplier $i$'s current strategic value regarding criteria/categories $j$ |
| $r_{\max}$ | Upper limit of a supplier's weight in the portfolio |
| $r_{\min}$ | Lower limit of a supplier's weight in the portfolio |
| $N_{\max}$ | Maximum number of suppliers that the buyer is willing to have |
| $N_{\min}$ | Minimum number of suppliers that the buyer is willing to have |
| $WM_j$ | The preferred value from the criterion/category $j$'s weight range |
| $R_{MtT}(\alpha; S_i)_j$ | MtT-type risk value from supplier $S_i$ regarding MtT-type risk $j$ at confidence level $\alpha$ if $S_i$ is the only supplier |
| $R_{VaR}(\alpha; S_i)_k$ | VaR-type risk value from supplier $S_i$ regarding VaR-type risk $k$ at confidence level $\alpha$ if $S_i$ is the only supplier |
| $R_{MtT}(S_i)_{Total}$ | The maximum possible loss from supplier $S_i$ if $S_i$ is the only supplier |

| | |
|---|---|
| $R_{MtT}(S_i)*$ | The sum of maximum possible MtT-type risk values $R_{MtT}(S_i)* = \sum_j R_{MtT}(\alpha; S_i)_j$ |

**Decision variables**

| | |
|---|---|
| $B_i$ | Binary variable assigned to each supplier. $B_i$ =1 implies supplier $i$ is selected and 0 otherwise |
| $n$ | Number of suppliers in the solution |
| $r_i$ | Supplier $i$ 's weight in the supply portfolio |
| $R_{VaR}(\alpha)$ | Supply portfolio's total VaR-type risk value at confidence level $\alpha$ |
| $PV_j(0)$ | Supplier portfolio's strategic value regarding criterion/category $j$ |
| $R_{MtT}(\alpha)$ | Supply portfolio's total MtT-type risk value at confidence level $\alpha$ |
| $R_{VaR}(\alpha; r_i)_k$ | Candidate $i$ 's VaR-type risk value regarding VaR risk type $k$ at confidence level $\alpha$ |
| $R_{MtT}(\alpha; r_i)$ | Total MtT-type risk from supplier $i$ at confidence level $\alpha$ |

**Model 1: Fuzzy Goal Programming Model**

In order to build the model, the following three single objective optimization sub-models need to be solved first to determine the best solution with respect to each objective, called the ***ideal solution***.

**Model 1.1:** Finding the best possible value for the portfolio's overall strategic value $PV(0)^*$

$$Max \quad PV(0) = \sum_j WM_j \times PV_j(0)$$

Subject to:

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\ j = 1, 2, ..., J$$

$$r_i \geq r_{\min} \times B_i \qquad \forall\ i = 1, 2, ..., I$$

$r_i \le r_{\max} \times B_i \qquad \forall\ i = 1, 2, ..., I$

$n = \sum_i B_i$

$n \le N_{\max}$

$n \ge N_{\min}$

$\sum_i r_i = 1$

$B_i = 0\ or\ 1 \qquad \forall\ i = 1, 2, ..., I$

Let $PV(0)*$ equal to the minimum value of $PV(0)$

**Model 1.2:** Finding the best possible value for the portfolio's VaR-type risk value $R_{VaR}(\alpha)^*$

$$Min \quad R_{VaR}(\alpha) = \sum_i \sum_k R_{VaR}(\alpha; r_i)_k$$

Subject to:

$R_{VaR}(\alpha; r_i)_k = R_{VaR}(\alpha; S_i)_k \times r_i$ ① $\qquad \forall\ k = 1, 2, ..., K\ \forall\ i = 1, 2, ..., I$

$r_i \ge r_{\min} \times B_i \qquad \forall\ i = 1, 2, ..., I$

$r_i \le r_{\max} \times B_i \qquad \forall\ i = 1, 2, ..., I$

$n = \sum_i B_i$

$n \le N_{\max}$

$n \ge N_{\min}$

$\sum_i r_i = 1$

$B_i = 0\ or\ 1 \qquad \forall\ i = 1, 2, ..., I$

①: The 2nd approximation method from section 4.5.4 is used here.

Let $R_{VaR}(\alpha)*$ equal to the minimum value of $R_{VaR}(\alpha)$

**Model 1.3:** Finding the best possible value for the portfolio's MtT-type risk value $R_{MtT}(\alpha)^*$

$$Min \quad R_{MtT}(\alpha) = \sum_i R_{MtT}(a; r_i)$$

Subject to:

$$R_{MtT}(a; r_i) = R_{MtT}(a; S_i) \times r_i \qquad \forall\, i = 1, 2, ..., I$$

$$R_{MtT}(a; S_i) = \sum_j R_{MtT}(\alpha; S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)^*} \qquad \forall\, i = 1, 2, ..., I$$

$$r_i \geq r_{\min} \times B_i \qquad \forall\, i = 1, 2, ..., I$$

$$r_i \leq r_{\max} \times B_i \qquad \forall\, i = 1, 2, ..., I$$

$$n = \sum_i B_i$$

$$n \leq N_{\max}$$

$$n \geq N_{\min}$$

$$\sum_i r_i = 1$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1, 2, ..., I$$

Let $R_{MtT}(\alpha)^*$ equal to the minimum value of $R_{MtT}(\alpha)$

Thus, the ideal solution is ( $PV(0)^*, R_{VaR}(\alpha)^*, R_{MtT}(\alpha)^*$ ). The fuzzy goal programming model minimizes the maximum deviation from the ideal solution. Let M equal the maximum deviation from the ideal solution. Then, the **fuzzy goal programming model** is as follows.

$$Min \quad M$$

Subject to:

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\; j = 1, 2, ..., J$$

$$M \geq \left( PV(0)^* - \sum_j WM_j \times PV_j(0) \right) \Big/ \lambda_1$$

$$R_{VaR}(\alpha;r_i)_k = R_{VaR}(\alpha;S_i)_k \times r_i \qquad \forall\, k = 1,2,...,K \;\forall\, i = 1,2,...,I$$

$$M \ge \left( \sum_i \sum_k R_{VaR}(\alpha;r_i)_k - R_{VaR}(\alpha)* \right) \Big/ \lambda_2$$

$$R_{MtT}(a;r_i) = R_{MtT}(a;S_i) \times r_i \qquad \forall\, i = 1,2,...,I$$

$$R_{MtT}(a;S_i) = \sum_j R_{MtT}(\alpha;S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)*} \qquad \forall\, i = 1,2,...,I$$

$$M \ge \left( \sum_i R_{MtT}(\alpha;r_i) - R_{MtT}(\alpha)^* \right) \Big/ \lambda_3$$

$$r_i \ge r_{\min} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$r_i \le r_{\max} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$n = \sum_i B_i$$

$$n \le N_{\max}$$

$$n \ge N_{\min}$$

$$\sum_i r_i = 1$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1,2,...,I$$

In the above model, $\lambda_1$, $\lambda_2$ and $\lambda_3$ are scaling constants to be set by the users. A common practice is to set the values of $\lambda_1$, $\lambda_2$ and $\lambda_3$ equal to the respective ideal values $PV(0)*$, $R_{VaR}(\alpha)*$ and $R_{MtT}(\alpha)*$.

**Model 2: Non-preemptive Goal Programming Model**

In the non-preemptive goal programming model, the buyer sets goals to achieve for each objective and preferences in achieving those goals expressed as numerical weights. Suppose that a buyer has the following three goals to meet and the weights of the goals are:

1. Limit the supplier portfolio’s VaR risk value to $R_{VaR}(\alpha)'$ with weight $W1$
2. Supplier portfolio’s current strategic value reaches $PV(0)'$ with weight $W2$
3. Limit the supplier portfolio’s MtT risk value to $R_{MtT}(\alpha)'$ with weight $W3$

Then, the non-preemptive goal programming model is:

$$Min \quad Z = W1 \times \frac{d_1^{+}}{R_{VaR}(\alpha)'} + W2 \times \frac{d_2^{-}}{PV(0)'} + W3 \times \frac{d_3^{+}}{R_{MtT}(\alpha)'}$$

Subject to:

$$R_{VaR}(\alpha;r_i)_k = R_{VaR}(\alpha;S_i)_k \times r_i \qquad \forall\, k = 1,2,...,K \ \forall\, i = 1,2,...,I$$

$$\sum_i \sum_k R_{VaR}(\alpha;r_i)_k + d_1^{-} - d_1^{+} = R_{VaR}(\alpha)'$$

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\, j = 1,2,...,J$$

$$\sum_j WM_j \times PV_j(0) + d_2^{-} - d_2^{+} = PV(0)'$$

$$R_{MtT}(a;r_i) = R_{MtT}(a;S_i) \times r_i \qquad \forall\, i = 1,2,...,I$$

$$R_{MtT}(a;S_i) = \sum_j R_{MtT}(\alpha;S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)*} \qquad \forall\, i = 1,2,...,I$$

$$\sum_i R_{MtT}(\alpha;r_i) + d3^{-} - d3^{+} = R_{VaR}(\alpha)'$$

$$r_i \geq r_{\min} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$r_i \leq r_{\max} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$n = \sum_i B_i$$

$$n \leq N_{\max}$$

$$n \geq N_{\min}$$

$$\sum_i r_i = 1$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1,2,...,I$$

Notes:

1. $d_1^{+}$, $d_2^{-}$ and $d_3^{+}$ represent non-achievement of stated goals.

2. Because numerical weights $W1$, $W2$, and $W3$ are used, the objectives should be scaled properly.

**Model 3: Preemptive Goal Programming Model**

Suppose that a buyer has three goals in the following priority order:

1. Limit the supplier portfolio's VaR risk value to $R_{VaR}(\alpha)'$
2. Supplier portfolio's current strategic value reaches $PV(0)'$
3. Limit the supplier portfolio's MtT risk value to $R_{MtT}(\alpha)'$

In this model, goals are achieved in the priority order specified, namely, meet VaR risk goal first, then strategic value goal, and MtT risk goal finally. The preemptive goal programming model is:

$$Min \quad Z = P_1 \times d_1^+ + P_2 \times d_2^- + P_3 \times d_3^+$$

Subject to:

$$R_{VaR}(\alpha; r_i)_k = R_{VaR}(\alpha; S_i)_k \times r_i \qquad \forall\, k = 1,2,...,K \ \forall\, i = 1,2,...,I$$

$$\sum_i \sum_k R_{VaR}(\alpha; r_i)_k + d_1^- - d_1^+ = R_{VaR}(\alpha)'$$

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\, j = 1,2,...,J$$

$$\sum_j WM_j \times PV_j(0) + d_2^- - d_2^+ = PV(0)'$$

$$R_{MtT}(a; r_i) = R_{MtT}(a; S_i) \times r_i \qquad \forall\, i = 1,2,...,I$$

$$R_{MtT}(a; S_i) = \sum_j R_{MtT}(\alpha; S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)*} \qquad \forall\, i = 1,2,...,I$$

$$\sum_i R_{MtT}(\alpha; r_i) + d3^- - d3^+ = R_{VaR}(\alpha)'$$

$$r_i \geq r_{\min} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$r_i \leq r_{\max} \times B_i \qquad \forall\, i = 1,2,...,I$$

$$n = \sum_i B_i$$

$$n \leq N_{\max}$$

$$n \geq N_{\min}$$

$$\sum_i r_i = 1$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1, 2, \ldots, I$$

Note: Because of the priority structure specified in achieving the goals, the goals do not have to be scaled. However, the optimization problem has to be scaled sequentially for each priority.

### 5.5. Choosing the final winner(s) (Step 5)

After Step 4, several solutions are available for senior managers to make the final decision. Their years' of experience and trained intuition can be fully utilized in this step. Usually, a meeting can be summoned and multiple decision makers could be involved. Several methods can be used to choose the winner.

#### Pair-wise comparison

Pair-wise comparison generally refers to any process of comparing entities in pairs to judge which of each pair is preferred, or has a greater amount of some quantitative property. The method of pairwise comparison is widely used in studies of preferences, voting, and multi-agent AI systems.

#### Delphi method

The Delphi method has traditionally been a technique aimed at building an agreement, or consensus about an opinion or view, without necessarily having people meet face to face, such as through surveys, questionnaires, e-mails etc.

To build consensus, the Delphi method often uses the Hegelian dialectic process of thesis (establishing an opinion or view), antithesis (conflicting opinion or view) and finally synthesis (a new agreement or consensus), with synthesis becoming the new thesis. All participants in the process then either change their views to align with the new thesis, or support the new thesis, to establish a new common view. The goal is a continual evolution towards 'oneness of mind' or consensus on the opinion or view.

### Borda count

The Borda count is a single winner election method in which voters rank candidates in order of preference. The Borda count determines the winner of an election by giving each candidate a certain number of points corresponding to the position in which he or she is ranked by each voter. Once all votes have been counted the candidate with the most points is the winner. Because it sometimes elects broadly acceptable candidates, rather than those preferred by the majority, the Borda count is often described as a consensus-based electoral system, rather than a majoritarian one.

### Voting using majority rule

This method is quite straightforward. If in the first round of voting, one of the alternatives receives more than half of the votes, it becomes the winner and the process stops. If none receives more than half the votes, the alternative with the fewest votes is dropped and then the second round of voting is carried out. This process will keep going until one of the alternatives receives more than half of the votes. One major problem about this method is that when the total number of votes is even, there could be a tie. Therefore, some tie-breaking rules should be established first.

## 5.6. Example

It this section, an example is given to illustrate how the 5-step strategic supplier selection method works.

Automobile manufacturer A needs headlight bulbs for its new sedan model which is supposed to stay in the market for 10 years. After some research, the procurement team of A found that in all there are 15 bulb manufacturers satisfy the basic requirements, and collected the related data about them.

### Step 1

After careful consideration, A decides that 14 criteria in 6 categories need to be considered in the selection process as shown in Table 5.2.

**Table 5.2 Company A's supplier selection criteria**

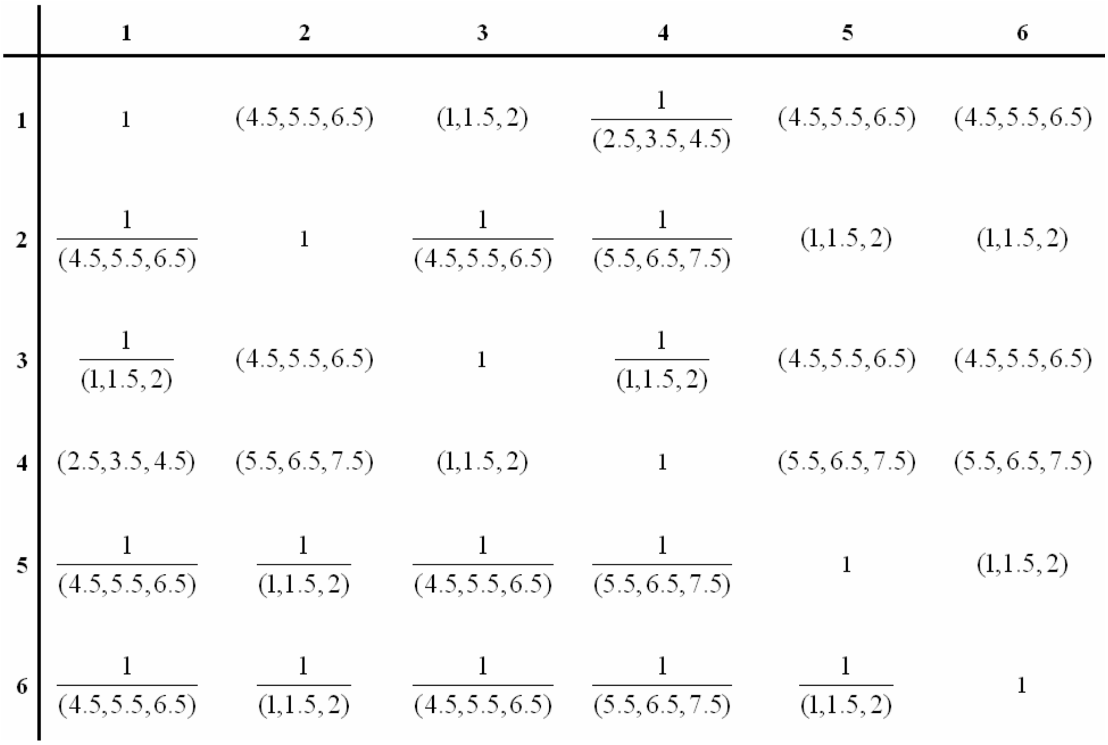
| No. | Category | Criterion |
|---|---|---|
| 1 | Delivery | Accuracy |
| | | Capacity |
| | | Lead time |
| 2 | Business Criteria | Financial status |
| | | Compatibility of long term business strategy |
| | | Location |
| 3 | Quality | Defective rate |
| | | Responsiveness of customer service |
| 4 | Cost | Unit cost |
| | | Order change and cancellation charges |
| 5 | Information Technology | Online |
| | | EDI |
| 6 | Long Term Improvement | Improvement programs |
| | | R&D abilities |

Then, A establishes its own linguistic descriptions for preference and the corresponding preference ranges are shown in Table 5.3. Table 5.4 shows the pair-wise comparison results of the 6 categories. For example, category 1 (Delivery) is strongly preferred to category 2 (Business Criteria). Categories 1 and 3 are equal. Between categories 1 and 4, category 4 is moderately preferred over category 1.

**Table 5.3 Linguistic description and preference range**

| Linguistic Description | Lower Bound | Medium | Upper Bound |
|---|---|---|---|
| Equal | 1 | 1 1/2 | 2 |
| Slightly preferred | 1 1/2 | 2 | 2 1/2 |
| Moderately preferred | 2 1/2 | 3 1/2 | 4 1/2 |
| Strongly preferred | 4 1/2 | 5 1/2 | 6 1/2 |
| Very strongly preferred | 5 1/2 | 6 1/2 | 7 1/2 |
| Extremely preferred | 7 1/2 | 8 1/2 | 9 1/2 |

**Table 5.4 Pair-wise comparison between 6 categories**



| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **1** | 1 | (4.5,5.5,6.5) | (1,1.5,2) | $\frac{1}{(2.5,3.5,4.5)}$ | (4.5,5.5,6.5) | (4.5,5.5,6.5) |
| **2** | $\frac{1}{(4.5,5.5,6.5)}$ | 1 | $\frac{1}{(4.5,5.5,6.5)}$ | $\frac{1}{(5.5,6.5,7.5)}$ | (1,1.5,2) | (1,1.5,2) |
| **3** | $\frac{1}{(1,1.5,2)}$ | (4.5,5.5,6.5) | 1 | $\frac{1}{(1,1.5,2)}$ | (4.5,5.5,6.5) | (4.5,5.5,6.5) |
| **4** | (2.5,3.5,4.5) | (5.5,6.5,7.5) | (1,1.5,2) | 1 | (5.5,6.5,7.5) | (5.5,6.5,7.5) |
| **5** | $\frac{1}{(4.5,5.5,6.5)}$ | $\frac{1}{(1,1.5,2)}$ | $\frac{1}{(4.5,5.5,6.5)}$ | $\frac{1}{(5.5,6.5,7.5)}$ | 1 | (1,1.5,2) |
| **6** | $\frac{1}{(4.5,5.5,6.5)}$ | $\frac{1}{(1,1.5,2)}$ | $\frac{1}{(4.5,5.5,6.5)}$ | $\frac{1}{(5.5,6.5,7.5)}$ | $\frac{1}{(1,1.5,2)}$ | 1 |

The lower bound for the sum of the first column is:

$$1+\frac{1}{6.5}+\frac{1}{2}+2.5+\frac{1}{6.5}+\frac{1}{6.5}=4.462$$

The sum of the preferred values of the first column is:

$$1+\frac{1}{5.5}+\frac{1}{1.5}+3.5+\frac{1}{5.5}+\frac{1}{5.5}=5.712$$

The upper bound for the sum of the first column is:

$$1+\frac{1}{4.5}+\frac{1}{1}+4.5+\frac{1}{4.5}+\frac{1}{4.5}=7.167$$

Similarly, we calculate the column sum range for columns 2 through 6. The sums of the columns are:

(4.462, 5.712, 7.167), (16.500, 19.833, 23.500), (3.462, 4.545, 5.667)
(2.122, 2.414, 2.945), (17.000, 20.667, 24.500), (17.500, 21.500, 25.500)

For column normalization, each range is divided by the sum of the preferred values of the column. For example, for $\frac{1}{(4.5, 5.5, 6.5)}$ in the first column, the normalized result is:

$$\frac{1}{(4.5, 5.5, 6.5)} / 5.712 = (\frac{1}{6.5} / 5.712, \frac{1}{5.5} / 5.712, \frac{1}{4.5} / 5.712) = (0.027, 0.032, 0.039)$$

Table 5.5 shows the results after normalizing Table 5.4. The lower bound for the average of the first row is:

$$\frac{0.175+0.227+0.220+0.092+0.218+0.209}{6} = 0.190$$

The average preferred value of the first row is:

$$\frac{0.175+0.277+0.330+0.118+0.266+0.256}{6} = 0.237$$

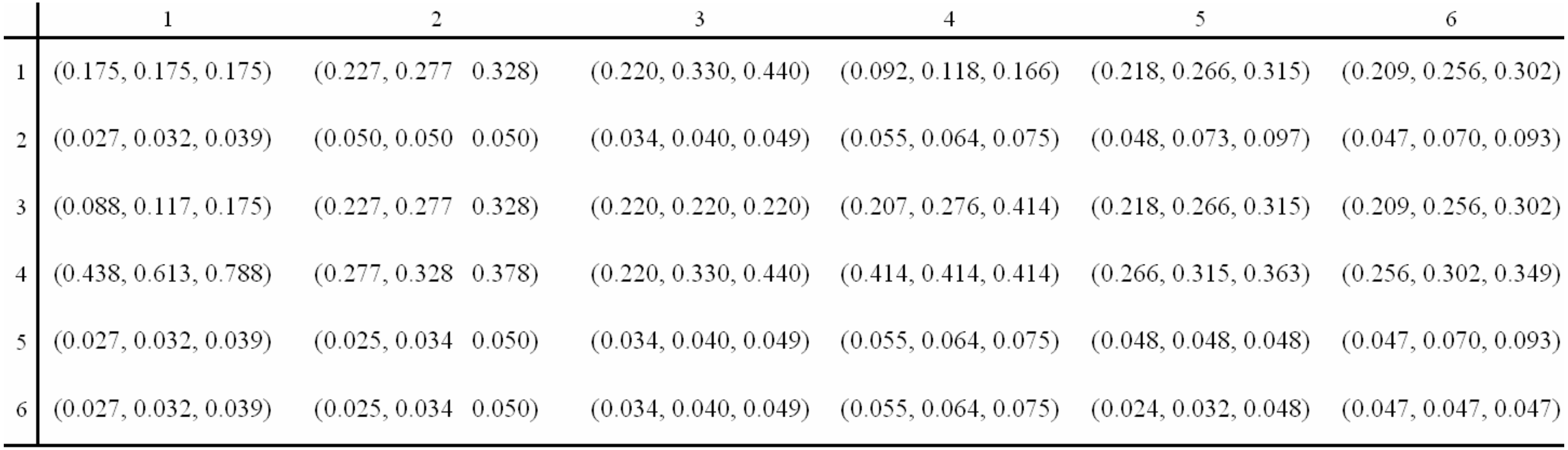
The upper bound for the average of the first row is:

$$\frac{0.175+0.328+0.440+0.166+0.315+0.302}{6} = 0.288$$

Similarly, we calculate the row average ranges for rows 2 through 6. The row averages are:

(0.190, 0.237, 0.288), (0.044, 0.055, 0.067), (0.195, 0.235, 0.292)
(0.312, 0.384, 0.455), (0.039, 0.048, 0.059), (0.035, 0.041, 0.051)

**Table 5.5 Normalized results from Table 5.4**



| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | (0.175, 0.175, 0.175) | (0.227, 0.277 0.328) | (0.220, 0.330, 0.440) | (0.092, 0.118, 0.166) | (0.218, 0.266, 0.315) | (0.209, 0.256, 0.302) |
| 2 | (0.027, 0.032, 0.039) | (0.050, 0.050 0.050) | (0.034, 0.040, 0.049) | (0.055, 0.064, 0.075) | (0.048, 0.073, 0.097) | (0.047, 0.070, 0.093) |
| 3 | (0.088, 0.117, 0.175) | (0.227, 0.277 0.328) | (0.220, 0.220, 0.220) | (0.207, 0.276, 0.414) | (0.218, 0.266, 0.315) | (0.209, 0.256, 0.302) |
| 4 | (0.438, 0.613, 0.788) | (0.277, 0.328 0.378) | (0.220, 0.330, 0.440) | (0.414, 0.414, 0.414) | (0.266, 0.315, 0.363) | (0.256, 0.302, 0.349) |
| 5 | (0.027, 0.032, 0.039) | (0.025, 0.034 0.050) | (0.034, 0.040, 0.049) | (0.055, 0.064, 0.075) | (0.048, 0.048, 0.048) | (0.047, 0.070, 0.093) |
| 6 | (0.027, 0.032, 0.039) | (0.025, 0.034 0.050) | (0.034, 0.040, 0.049) | (0.055, 0.064, 0.075) | (0.024, 0.032, 0.048) | (0.047, 0.047, 0.047) |

This means the weight range for category “Delivery” is $(0.190, 0.237, 0.288)$, the weight range for category “Business Criteria” is $(0.044, 0.055, 0.067)$, the weight range for category “Quality” is $(0.195, 0.235, 0.292)$, the weight range for category “Cost” is $(0.312, 0.384, 0.455)$, the weight for category “Information Technology” is $(0.039, 0.048, 0.059)$, and the weight for the last category “Long-Term Improvement” is $(0.035, 0.041, 0.051)$.

Table 5.6 shows the pair-wise comparison results of the three criteria in category “Delivery”.

**Table 5.6 Pair-wise comparison for the criteria in category “Delivery”**

| | **Accuracy** | **Capacity** | **Lead Time** |
|---|---|---|---|
| **Accuracy** | 1 | $(4.5, 5.5, 6.5)$ | $(2.5, 3.5, 4.5)$ |
| **Capacity** | $\frac{1}{(4.5, 5.5, 6.5)}$ | 1 | $\frac{1}{(1, 1.5, 2)}$ |
| **Lead Time** | $\frac{1}{(2.5, 3.5, 4.5)}$ | $(1, 1.5, 2)$ | 1 |

The sums of the columns are:

(1.376, 1.468, 1.622), (6.500, 8.000, 9.500), (4.000, 5.167, 6.500)

After column normalization, the row averages are:

(0.576, 0.682, 0.788), (0.109, 0.126, 0.157), (0.157, 0.192, 0.239)

Table 5.7 shows the pair-wise comparison results of the 3 criteria in category “Business Criteria”.

**Table 5.7 Pair-wise comparison for the criteria in category “Business Criteria”**

| | Financial Status | Compatibility | Location |
|---|---|---|---|
| **Financial Status** | 1 | $(4.5, 5.5, 6.5)$ | $(1.5, 2, 2.5)$ |
| **Compatibility** | $\frac{1}{(4.5, 5.5, 6.5)}$ | 1 | $\frac{1}{(2.5, 3.5, 4.5)}$ |
| **Location** | $\frac{1}{(1.5, 2, 2.5)}$ | $(2.5, 3.5, 4.5)$ | 1 |

The sums of the columns are:

(1.554, 1.682, 1.889), (8.000, 10.000, 12.000), (2.722, 3.286, 3.900)

After column normalization, the row averages are:

(0.500, 0.584, 0.668), (0.086, 0.098, 0.118), (0.264, 0.317, 0.384)

There is no need to do pair-wise comparison for other categories since all of them only have 2 criteria. A assigns

- (0.650,0.700,0.750) and (0.250,0.300,0.350) to criteria “defective rate” and “the responsiveness of customer service”,
- (0.650, 0.750, 0.850) and (0.150, 0.250, 0.350) to criteria “unit cost” and “order change and cancellation charges”,
- (0.400, 0.500, 0.600) and (0.400, 0.500, 0.600) to criteria “Online” and “EDI”,
- (0.550, 0.600, 0.650) and (0.350, 0.400, 0.450) to criteria “Improvement programs” and “R&D abilities”.

Then, the weight ranges for all 14 criteria are shown in Figure 5.2.

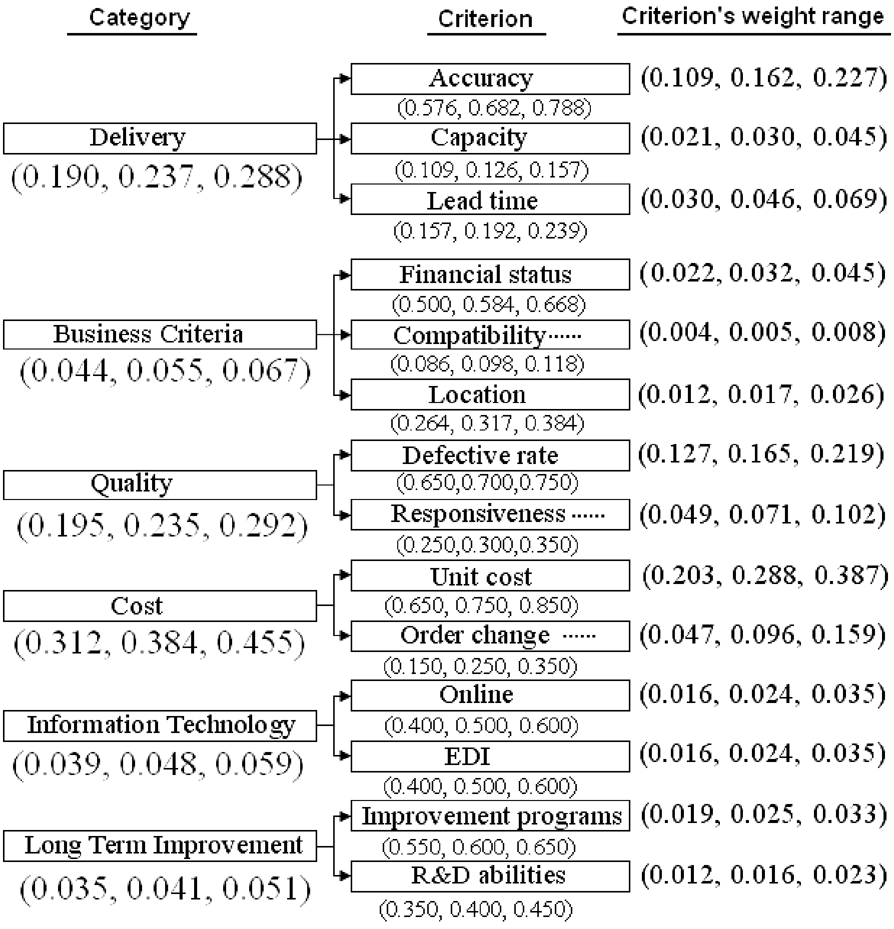


**Figure 5.2 Weight ranges of categories and criteria**

**Step 2**

Table 5.8 shows the 15 candidates' current performance score for each criterion which ranges from 0 to 10. Table 5.9 shows the normalized score using following equation.

$$Normalized\ Score = \frac{Score}{Column\ Max}$$

Table 5.10 shows the $\frac{1+g}{1+k}$ value for each supplier for each criterion. Then, the current strategic values can be calculated and the results are shown in Table 5.11. Table 5.12 shows the normalized current strategic values by using the following equation.

$$Normalized\ Current\ Strategic\ Value = \frac{Current\ Strategic\ Value}{Column\ Max}$$

**Table 5.8 Potential suppliers’ scores regarding each criterion**

| | | **Criteria** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| **Suppliers** | **1** | 4.781 | 9.061 | 2.608 | 0.120 | 5.485 | 3.216 | 9.276 | 4.866 | 7.243 | 1.454 | 6.922 | 3.531 | 5.040 | 5.341 |
| | **2** | 2.069 | 7.275 | 8.263 | 0.174 | 4.483 | 8.775 | 9.085 | 9.570 | 5.081 | 1.854 | 2.533 | 5.172 | 1.509 | 5.063 |
| | **3** | 4.502 | 7.775 | 0.511 | 0.151 | 6.827 | 5.941 | 0.065 | 8.203 | 5.434 | 4.202 | 8.858 | 1.728 | 3.744 | 5.855 |
| | **4** | 5.192 | 6.338 | 7.885 | 3.478 | 6.762 | 6.344 | 4.369 | 3.594 | 8.747 | 7.233 | 6.863 | 8.248 | 1.449 | 0.731 |
| | **5** | 8.270 | 8.442 | 1.433 | 9.671 | 7.023 | 6.144 | 1.075 | 3.866 | 2.028 | 6.401 | 3.603 | 2.692 | 4.320 | 8.315 |
| | **6** | 9.357 | 6.138 | 3.834 | 8.821 | 4.723 | 0.072 | 6.829 | 6.658 | 9.105 | 5.110 | 9.195 | 6.430 | 8.498 | 9.271 |
| | **7** | 1.735 | 7.144 | 9.963 | 5.807 | 3.505 | 1.527 | 8.015 | 2.291 | 3.741 | 1.885 | 3.009 | 1.574 | 1.117 | 1.427 |
| | **8** | 3.413 | 7.763 | 6.371 | 1.720 | 2.103 | 7.425 | 0.085 | 3.024 | 7.449 | 6.046 | 6.531 | 0.711 | 5.143 | 9.004 |
| | **9** | 6.722 | 7.190 | 3.474 | 8.942 | 9.178 | 4.821 | 8.911 | 6.323 | 5.423 | 2.968 | 9.107 | 2.854 | 3.598 | 9.428 |
| | **10** | 4.330 | 9.927 | 0.479 | 1.477 | 7.839 | 1.764 | 4.096 | 1.651 | 9.574 | 2.189 | 2.770 | 9.108 | 0.590 | 9.392 |
| | **11** | 1.355 | 5.170 | 7.689 | 2.884 | 3.399 | 6.840 | 2.552 | 9.423 | 0.433 | 8.738 | 1.859 | 0.774 | 6.608 | 4.942 |
| | **12** | 7.459 | 6.916 | 4.461 | 1.792 | 7.293 | 5.124 | 5.993 | 9.128 | 8.344 | 7.871 | 1.062 | 8.214 | 9.017 | 2.007 |
| | **13** | 1.515 | 4.266 | 2.622 | 0.133 | 9.116 | 2.204 | 8.595 | 8.915 | 5.458 | 2.071 | 7.618 | 7.440 | 0.986 | 4.037 |
| | **14** | 4.710 | 9.150 | 7.937 | 9.020 | 5.892 | 4.254 | 0.039 | 2.219 | 3.638 | 9.102 | 1.134 | 7.240 | 3.389 | 2.207 |
| | **15** | 2.923 | 5.867 | 0.895 | 7.831 | 3.962 | 3.787 | 0.228 | 1.647 | 2.055 | 3.758 | 0.502 | 7.744 | 7.712 | 5.736 |

**Table 5.9 Normalized scores**

| | | Criteria | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| **Suppliers** | **1** | 0.511 | 0.913 | 0.262 | 0.012 | 0.598 | 0.366 | 1.000 | 0.508 | 0.757 | 0.160 | 0.753 | 0.388 | 0.553 | 0.567 |
| | **2** | 0.221 | 0.733 | 0.829 | 0.018 | 0.598 | 1.000 | 0.979 | 1.000 | 0.531 | 0.204 | 0.275 | 0.568 | 0.166 | 0.537 |
| | **3** | 0.481 | 0.783 | 0.051 | 0.016 | 0.598 | 0.677 | 0.007 | 0.857 | 0.568 | 0.462 | 0.963 | 0.190 | 0.411 | 0.621 |
| | **4** | 0.555 | 0.638 | 0.791 | 0.360 | 0.598 | 0.723 | 0.471 | 0.376 | 0.914 | 0.795 | 0.746 | 0.906 | 0.159 | 0.078 |
| | **5** | 0.884 | 0.850 | 0.144 | 1.000 | 0.598 | 0.700 | 0.116 | 0.404 | 0.212 | 0.703 | 0.392 | 0.296 | 0.474 | 0.882 |
| | **6** | 1.000 | 0.618 | 0.385 | 0.912 | 0.598 | 0.008 | 0.736 | 0.696 | 0.951 | 0.561 | 1.000 | 0.706 | 0.933 | 0.983 |
| | **7** | 0.185 | 0.720 | 1.000 | 0.600 | 0.598 | 0.174 | 0.864 | 0.239 | 0.391 | 0.207 | 0.327 | 0.173 | 0.123 | 0.151 |
| | **8** | 0.365 | 0.782 | 0.639 | 0.178 | 0.598 | 0.846 | 0.009 | 0.316 | 0.778 | 0.664 | 0.710 | 0.078 | 0.565 | 0.955 |
| | **9** | 0.718 | 0.724 | 0.349 | 0.925 | 0.598 | 0.549 | 0.961 | 0.661 | 0.566 | 0.326 | 0.990 | 0.313 | 0.395 | 1.000 |
| | **10** | 0.463 | 1.000 | 0.048 | 0.153 | 0.598 | 0.201 | 0.442 | 0.173 | 1.000 | 0.240 | 0.301 | 1.000 | 0.065 | 0.996 |
| | **11** | 0.145 | 0.521 | 0.772 | 0.298 | 0.598 | 0.779 | 0.275 | 0.985 | 0.045 | 0.960 | 0.202 | 0.085 | 0.726 | 0.524 |
| | **12** | 0.797 | 0.697 | 0.448 | 0.185 | 0.598 | 0.584 | 0.646 | 0.954 | 0.872 | 0.865 | 0.115 | 0.902 | 0.990 | 0.213 |
| | **13** | 0.162 | 0.430 | 0.263 | 0.014 | 0.598 | 0.251 | 0.927 | 0.932 | 0.570 | 0.228 | 0.828 | 0.817 | 0.108 | 0.428 |
| | **14** | 0.503 | 0.922 | 0.797 | 0.933 | 0.598 | 0.485 | 0.004 | 0.232 | 0.380 | 1.000 | 0.123 | 0.795 | 0.372 | 0.234 |
| | **15** | 0.312 | 0.591 | 0.090 | 0.810 | 0.598 | 0.432 | 0.025 | 0.172 | 0.215 | 0.413 | 0.055 | 0.850 | 0.847 | 0.608 |

**Table 5.10 Discounted improvement rate of each candidate regarding each criterion**

| | | Criteria | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| | **1** | 0.986 | 1.074 | 0.989 | 1.104 | 1.023 | 0.988 | 1.116 | 0.999 | 1.121 | 0.921 | 1.097 | 0.972 | 0.955 | 0.967 |
| | **2** | 1.035 | 1.049 | 0.951 | 1.000 | 1.007 | 1.093 | 0.997 | 1.016 | 1.003 | 1.018 | 1.062 | 0.959 | 0.933 | 1.000 |
| | **3** | 0.961 | 1.123 | 1.023 | 1.102 | 1.117 | 0.952 | 1.119 | 1.071 | 1.104 | 1.014 | 1.092 | 0.972 | 1.017 | 0.924 |
| | **4** | 1.090 | 1.069 | 1.078 | 1.103 | 1.050 | 1.031 | 1.002 | 1.039 | 0.957 | 1.038 | 1.084 | 1.049 | 1.097 | 1.085 |
| | **5** | 1.015 | 0.997 | 1.010 | 0.951 | 1.001 | 1.100 | 0.940 | 0.996 | 0.933 | 0.988 | 0.980 | 0.985 | 1.012 | 0.936 |
| | **6** | 0.936 | 0.985 | 1.041 | 0.949 | 1.011 | 0.971 | 1.117 | 1.089 | 0.924 | 1.073 | 1.073 | 0.938 | 1.065 | 0.998 |
| | **7** | 1.087 | 1.123 | 1.111 | 0.927 | 1.098 | 1.116 | 1.076 | 0.923 | 0.925 | 0.997 | 1.104 | 1.023 | 1.029 | 1.033 |
| **Suppliers** | **8** | 0.924 | 1.069 | 1.118 | 1.035 | 1.056 | 0.959 | 0.927 | 1.087 | 0.945 | 0.930 | 0.971 | 1.117 | 0.949 | 1.064 |
| | **9** | 1.063 | 0.939 | 0.990 | 1.045 | 1.084 | 0.977 | 0.979 | 1.075 | 1.102 | 1.103 | 0.999 | 1.034 | 1.019 | 1.012 |
| | **10** | 0.986 | 0.938 | 1.047 | 1.114 | 1.066 | 1.010 | 1.111 | 1.085 | 1.120 | 1.122 | 1.018 | 1.057 | 0.921 | 1.107 |
| | **11** | 1.016 | 0.986 | 1.089 | 0.970 | 1.121 | 1.075 | 1.098 | 1.051 | 1.042 | 1.122 | 1.034 | 1.077 | 0.947 | 0.986 |
| | **12** | 1.041 | 1.046 | 1.101 | 0.937 | 1.117 | 1.088 | 0.946 | 1.054 | 1.089 | 1.122 | 1.102 | 0.960 | 0.976 | 1.057 |
| | **13** | 1.120 | 1.097 | 1.066 | 1.066 | 0.997 | 1.095 | 1.090 | 0.959 | 0.941 | 0.942 | 1.112 | 0.926 | 1.088 | 1.088 |
| | **14** | 1.085 | 0.983 | 0.957 | 1.061 | 1.096 | 0.929 | 1.065 | 1.058 | 0.950 | 1.022 | 1.067 | 1.055 | 1.108 | 1.087 |
| | **15** | 0.983 | 0.943 | 0.930 | 1.106 | 1.122 | 1.061 | 1.047 | 1.090 | 1.077 | 1.054 | 1.090 | 0.974 | 1.005 | 1.058 |

**Table 5.11 Candidates' strategic values regarding each criterion**

| | | Criteria | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| **Suppliers** | **1** | 4.799 | 12.852 | 2.492 | 0.202 | 6.634 | 3.473 | 17.213 | 5.062 | 13.340 | 1.134 | 11.826 | 3.423 | 4.538 | 4.894 |
| | **2** | 2.594 | 9.175 | 6.685 | 0.180 | 6.168 | 15.412 | 9.663 | 10.752 | 5.379 | 2.210 | 3.665 | 4.738 | 1.237 | 5.370 |
| | **3** | 4.049 | 13.945 | 0.569 | 0.251 | 10.337 | 5.480 | 0.122 | 11.899 | 9.221 | 4.919 | 14.777 | 1.675 | 4.440 | 4.464 |
| | **4** | 8.430 | 8.780 | 11.357 | 5.815 | 7.517 | 8.326 | 4.753 | 4.488 | 7.557 | 9.453 | 11.020 | 11.337 | 2.500 | 1.150 |
| | **5** | 9.459 | 8.390 | 1.505 | 8.060 | 6.003 | 11.159 | 0.891 | 3.968 | 1.581 | 6.665 | 3.584 | 2.764 | 5.008 | 6.668 |
| | **6** | 7.560 | 5.782 | 4.642 | 7.289 | 6.281 | 0.072 | 12.733 | 10.520 | 6.837 | 7.868 | 14.014 | 5.383 | 12.592 | 9.745 |
| | **7** | 2.777 | 12.814 | 16.803 | 4.371 | 9.434 | 2.995 | 12.282 | 1.714 | 2.821 | 2.043 | 5.317 | 1.918 | 1.400 | 1.759 |
| | **8** | 2.622 | 10.754 | 11.114 | 2.086 | 7.731 | 7.059 | 0.067 | 4.733 | 6.112 | 4.897 | 6.244 | 1.350 | 4.513 | 12.827 |
| | **9** | 9.603 | 5.546 | 3.334 | 11.362 | 8.824 | 4.959 | 8.748 | 9.347 | 9.114 | 5.272 | 9.860 | 3.659 | 4.306 | 10.558 |
| | **10** | 4.347 | 7.625 | 0.596 | 2.604 | 8.103 | 2.103 | 7.420 | 2.559 | 17.549 | 4.261 | 3.269 | 12.997 | 0.460 | 16.419 |
| | **11** | 1.557 | 4.892 | 11.669 | 2.610 | 10.538 | 11.027 | 4.343 | 12.443 | 0.548 | 17.011 | 2.361 | 1.214 | 5.749 | 4.924 |
| | **12** | 9.615 | 8.601 | 7.170 | 1.407 | 10.337 | 8.787 | 5.097 | 12.223 | 13.178 | 15.323 | 1.858 | 7.557 | 8.897 | 2.767 |
| | **13** | 2.841 | 6.751 | 3.568 | 0.186 | 5.896 | 3.908 | 14.078 | 7.772 | 4.402 | 1.765 | 13.988 | 5.922 | 1.629 | 6.444 |
| | **14** | 7.467 | 8.543 | 6.589 | 12.351 | 9.344 | 3.559 | 0.057 | 3.028 | 3.049 | 11.050 | 1.680 | 10.235 | 6.163 | 3.506 |
| | **15** | 2.895 | 4.603 | 0.662 | 13.282 | 10.590 | 5.715 | 0.305 | 2.615 | 3.066 | 5.291 | 0.829 | 7.574 | 8.661 | 7.944 |

**Table 5.12 Normalized strategic values**

| | | Criteria | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| **Suppliers** | **1** | 0.499 | 0.922 | 0.148 | 0.015 | 0.626 | 0.225 | 1.000 | 0.407 | 0.760 | 0.067 | 0.800 | 0.263 | 0.360 | 0.298 |
| | **2** | 0.270 | 0.658 | 0.398 | 0.014 | 0.582 | 1.000 | 0.561 | 0.864 | 0.307 | 0.130 | 0.248 | 0.365 | 0.098 | 0.327 |
| | **3** | 0.421 | 1.000 | 0.034 | 0.019 | 0.976 | 0.356 | 0.007 | 0.956 | 0.525 | 0.289 | 1.000 | 0.129 | 0.353 | 0.272 |
| | **4** | 0.877 | 0.630 | 0.676 | 0.438 | 0.710 | 0.540 | 0.276 | 0.361 | 0.431 | 0.556 | 0.746 | 0.872 | 0.199 | 0.070 |
| | **5** | 0.984 | 0.602 | 0.090 | 0.607 | 0.567 | 0.724 | 0.052 | 0.319 | 0.090 | 0.392 | 0.243 | 0.213 | 0.398 | 0.406 |
| | **6** | 0.786 | 0.415 | 0.276 | 0.549 | 0.593 | 0.005 | 0.740 | 0.845 | 0.390 | 0.462 | 0.948 | 0.414 | 1.000 | 0.594 |
| | **7** | 0.289 | 0.919 | 1.000 | 0.329 | 0.891 | 0.194 | 0.714 | 0.138 | 0.161 | 0.120 | 0.360 | 0.148 | 0.111 | 0.107 |
| | **8** | 0.273 | 0.771 | 0.661 | 0.157 | 0.730 | 0.458 | 0.004 | 0.380 | 0.348 | 0.288 | 0.423 | 0.104 | 0.358 | 0.781 |
| | **9** | 0.999 | 0.398 | 0.198 | 0.855 | 0.833 | 0.322 | 0.508 | 0.751 | 0.519 | 0.310 | 0.667 | 0.282 | 0.342 | 0.643 |
| | **10** | 0.452 | 0.547 | 0.035 | 0.196 | 0.765 | 0.136 | 0.431 | 0.206 | 1.000 | 0.251 | 0.221 | 1.000 | 0.037 | 1.000 |
| | **11** | 0.162 | 0.351 | 0.694 | 0.197 | 0.995 | 0.716 | 0.252 | 1.000 | 0.031 | 1.000 | 0.160 | 0.093 | 0.457 | 0.300 |
| | **12** | 1.000 | 0.617 | 0.427 | 0.106 | 0.976 | 0.570 | 0.296 | 0.982 | 0.751 | 0.901 | 0.126 | 0.581 | 0.707 | 0.169 |
| | **13** | 0.296 | 0.484 | 0.212 | 0.014 | 0.557 | 0.254 | 0.818 | 0.625 | 0.251 | 0.104 | 0.947 | 0.456 | 0.129 | 0.392 |
| | **14** | 0.777 | 0.613 | 0.392 | 0.930 | 0.882 | 0.231 | 0.003 | 0.243 | 0.174 | 0.650 | 0.114 | 0.787 | 0.489 | 0.214 |
| | **15** | 0.301 | 0.330 | 0.039 | 1.000 | 1.000 | 0.371 | 0.018 | 0.210 | 0.175 | 0.311 | 0.056 | 0.583 | 0.688 | 0.484 |

**Step 3**

Following is the FWBR model that enables A to find out the best possible rank for supplier 1.

$$Min \quad Z = \sum_i B_i$$

Subject to:

$$WL_j \le W_j \le WU_j \qquad \forall j = 1, 2, \ldots, 14$$

$$\sum_j W_j = 1$$

$$P_i \ge 0 \qquad \forall i = 1, 2, \ldots, 15$$

$$N_i \ge 0 \qquad \forall i = 1, 2, \ldots, 15$$

$$B_i = 0 \; or \; 1 \qquad \forall i = 1, 2, \ldots, 15$$

$$V_i = \sum_j W_j \times V_{(i,j)}(0) \qquad \forall i = 1, 2, \ldots, 15$$

$$V_i - V_s = P_i - N_i \qquad \forall i = 2, 3, \ldots, 15$$

$$B_i \times M \ge P_i \qquad \forall i = 2, 3, \ldots, 15$$

$$M = 1000$$

$WL_j$ and $WU_j$ are shown in Figure 5.2. Table 5.12 has all the values for $V_{(i,j)}(0)$. The FWBR model is solved separately for each supplier from 1 to 15. Appendix A shows the LINGO code for the FWBR model. By setting S in the code from 1 to 15, A can find the best possible rank for each candidate as shown in Table 5.13.

**Table 5.13 Best possible rank for each candidate**

| Candidate | Best Possible Rank |
|---|---|
| 1 | 1st |
| 2 | 7th |
| 3 | 7th |
| 4 | 3rd |
| 5 | 7th |
| 6 | 2nd |
| 7 | 7th |
| 8 | 10th |
| 9 | 2nd |
| 10 | 2nd |
| 11 | 7th |
| 12 | 1st |
| 13 | 7th |
| 14 | 7th |
| 15 | 14th |

Since A is only willing to consider candidates in the top3 ranking, candidates 1, 4, 6, 9, 10, and 12 enter step 4.

## Step 4

A decides that no supplier with a weight more than 80% will be included in its supply portfolio, and also no supplier with a weight less than 10%. A has also decided that at least 2 but no more than 3 suppliers will be selected.

### Fuzzy Goal Programming Model

### Sub model I

Following is the model to find out the best possible value for the portfolio's overall strategic value.

$$Max \quad PV(0) = \sum_j WM_j \times PV_j(0)$$

Subject to:

$$\begin{array}{ll}
PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) & \forall j = 1,2,...,14 \ \& \ i = 1,4,6,9,10,12 \\
0.8 \times B_i \geq r_i \geq 0.1 \times B_i & \forall\ i = 1,4,6,9,10,12 \\
3 \geq \sum_i B_i \geq 2 & i = 1,4,6,9,10,12 \\
\sum_i r_i = 1 & i = 1,4,6,9,10,12 \\
B_i = 0 \ or \ 1 & \forall\ i = 1,4,6,9,10,12
\end{array}$$

Note: $WM_j$ are the preferred values of the criteria obtained from Figure 5.2.

Solution: $Max\ PV(0) = PV(0)^* = 0.658$

Appendix B is the LINGO code for this model. After solving the model, A finds that the best result it can get is 0.658 with supplier 1 and 12. In the portfolio, supplier 1's weight is 0.2 and supplier 12's weight is 0.8.

**Sub model II**

A sets confidence level $\alpha$ to 0.95. After doing some analysis, A finds that there are in total 8 different VaR type risks it should worry about from suppliers. By simulation, A gets $R_{VaR}(0.95;S_i)_k$ as shown in Table 5.14 for candidates 1, 4, 6, 9, 10, and 12.

**Table 5.14 VaR-type risks values from selected candidates (unit: dollar)**

| | Candidate | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 4 | 6 | 9 | 10 | 12 |
| VaR 1 | 170088 | 431866 | 479128 | 720291 | 761967 | 793268 |
| VaR 2 | 312361 | 262672 | 41594 | 505476 | 729005 | 475574 |
| VaR 3 | 856277 | 382681 | 806438 | 57087 | 364999 | 168048 |
| VaR 4 | 456607 | 913594 | 652810 | 774618 | 341736 | 64823 |
| VaR 5 | 994049 | 85338 | 317794 | 265372 | 167593 | 726894 |
| VaR 6 | 677506 | 773350 | 523222 | 173655 | 349698 | 156717 |
| VaR 7 | 715589 | 525002 | 632578 | 482478 | 915065 | 745854 |
| VaR 8 | 711658 | 982026 | 477717 | 296643 | 729063 | 447705 |

Following is the model to find out the best possible value for the portfolio's overall VaR type risk.

$$Min \quad R_{VaR}(0.95) = \sum_i \sum_k R_{VaR}(0.95;r_i)_k$$

Subject to:

$$R_{VaR}(0.95;r_i)_k = R_{VaR}(0.95;S_i)_k \times r_i \qquad \forall\, k = 1,2,...,5 \;\forall\, i = 1,4,6,9,10,12$$

$$r_{\min} \times B_i \le r_i \le r_{\max} \times B_i \qquad \forall\, i = 1,4,6,9,10,12$$

$$2 \le \sum_i B_i \le 3 \qquad i = 1,4,6,9,10,12$$

$$\sum_i r_i = 1 \qquad i = 1,4,6,9,10,12$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1,4,6,9,10,12$$

Solution: $Min\ R_{VaR}(0.95) = R_{VaR}(0.95)^* = \$3{,}336{,}273$

Appendix C is the LINGO code for this model. After solving the model, A finds that the best result it can get is \$3,336,273 with supplier 9 and 12. In the portfolio, supplier 9’s weight is 0.8 and supplier 12’s weight is 0.2.

**Sub model III**

After data collection and analysis as well as some simulations, A finds $R_{MtT}(\alpha;S_i)_j$ and $\frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)^*}$ as shown in Table 5.15 for candidate 1, 4, 6, 9, 10, and 12.

**Table 5.15 MtT-type risk related data for selected candidates**

| | | Candidates | | | | | |
|---|---|---|---|---|---|---|---|
| | | **1** | **4** | **6** | **9** | **10** | **12** |
| $R_{MtT}(\alpha;S_i)_j$ | 1 | \$76,464 | \$129,005 | \$60,080 | \$56,366 | \$116,165 | \$97,884 |
| | 2 | \$40,703 | \$81,192 | \$76,224 | \$116,960 | \$77,830 | \$106,148 |
| | 3 | \$61,997 | \$107,928 | \$118,320 | \$87,833 | \$109,935 | \$87,644 |
| | 4 | \$120,973 | \$76,173 | \$90,202 | \$47,017 | \$121,981 | \$105,769 |
| | 5 | \$31,509 | \$124,227 | \$120,921 | \$98,075 | \$39,006 | \$82,332 |
| | 6 | \$88,737 | \$84,890 | \$79,655 | \$44,541 | \$55,381 | \$91,996 |
| | 7 | \$30,408 | \$126,871 | \$49,115 | \$56,334 | \$51,579 | \$126,848 |
| | 8 | \$90,403 | \$53,579 | \$129,431 | \$124,177 | \$33,552 | \$55,879 |
| | 9 | \$90,840 | \$35,571 | \$96,015 | \$69,847 | \$51,615 | \$74,479 |
| | 10 | \$109,676 | \$73,556 | \$32,911 | \$79,154 | \$113,314 | \$87,085 |
| | 11 | \$72,949 | \$85,291 | \$112,319 | \$99,579 | \$111,371 | \$72,217 |
| | 12 | \$41,532 | \$65,755 | \$40,898 | \$96,752 | \$50,163 | \$83,546 |
| | 13 | \$61,666 | \$78,132 | \$64,189 | \$116,231 | \$44,294 | \$90,886 |
| | 14 | \$95,891 | \$83,143 | \$99,550 | \$109,450 | \$121,337 | \$128,787 |
| $\frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)^*}$ | | **0.85** | **0.71** | **0.77** | **0.69** | **0.74** | **0.87** |

Following is the model to find out the best possible value for the portfolio's overall MtT-type risk.

$$Min \quad R_{MtT}(0.95) = \sum_i R_{MtT}(0.95; r_i)$$

subject to:

$$R_{MtT}(0.95; r_i) = R_{MtT}(0.95; S_i) \times r_i \qquad \forall\, i = 1,4,6,9,10,12$$

$$R_{MtT}(0.95; S_i) = \sum_j R_{MtT}(0.95; S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)^*} \qquad \forall\, i = 1,4,6,9,10,12$$

$$r_{\min} \times B_i \le r_i \le r_{\max} \times B_i \qquad \forall\, i = 1,4,6,9,10,12$$

$$2 \le \sum_i B_i \le 3 \qquad i = 1,4,6,9,10,12$$

$$\sum_i r_i = 1 \qquad i = 1,4,6,9,10,12$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1,4,6,9,10,12$$

Solution: $Min\ R_{MtT}(0.95) = R_{MtT}(0.95)^* = \$815,653$

Appendix D is the LINGO code for this model. After solving the model, A finds that the best result it can get is $815,653 with supplier 9 and 10. In the portfolio, supplier 9'weight is 0.2 and supplier 10's weight is 0.8.

After solving the above three sub models, A knows that the ideal values of the objectives are:

$$PV(0)^* = 0.658$$

$$R_{VaR}(0.95)^* = \$3,336,273$$

$$R_{MtT}(0.95)^* = \$815,653$$

Following is the fuzzy goal programming model.

$$Min \quad M$$

subject to:

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\ j = 1, 2, ..., 14$$

$$M \geq \left( 0.658 - \sum_j WM_j \times PV_j(0) \right) \times 1000$$

$$R_{VaR}(0.95; r_i)_k = R_{VaR}(0.95; S_i)_k \times r_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12 \,\&\, K = 1, 2, ..., 8$$

$$M \geq \left( \sum_i \sum_k R_{VaR}(0.95; r_i)_k - 3336273 \right) \Big/ 10000 \qquad i = 1, 4, 6, 9, 10, 12$$

$$R_{MtT}(0.95; r_i) = R_{MtT}(0.95; S_i) \times r_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$R_{MtT}(0.95; S_i) = \sum_j R_{MtT}(0.95; S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)^*} \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$M \geq \left( \sum_i R_{MtT}(0.95; r_i) - 815653 \right) \Big/ 1000 \qquad i = 1, 4, 6, 9, 10, 12$$

$$r_{\min} \times B_i \leq r_i \leq r_{\max} \times B_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$2 \leq \sum_i B_i \leq 3 \qquad i = 1, 4, 6, 9, 10, 12$$

$$\sum_i r_i = 1 \qquad i = 1, 4, 6, 9, 10, 12$$

$$B_i = 0 \; or \; 1 \qquad \forall\, i = 1, 4, 6, 9, 10, 12$$

Note: The scaling constants used for the three objectives are

$$\lambda_1 = 1/1000 \quad \lambda_2 = 10{,}000 \quad \lambda_3 = 1000$$

Appendix E is the LINGO code for this model. After solving the model, A finds that the best portfolio consists of suppliers 9 and 12, and their weights are 0.741 and 0.159.

**Non-preemptive Goal Programming Model**

Following is the model.

$$Min \quad Z = W1 \times \frac{d_1^{+}}{3336273} + W2 \times \frac{d_2^{-}}{0.658} + W3 \times \frac{d_3^{+}}{815653}$$

subject to:

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\ j = 1,2,\ldots,14$$

$$R_{VaR}(0.95;r_i)_k = R_{VaR}(0.95;S_i)_k \times r_i \qquad \forall\ i = 1,4,6,9,10,12 \,\&\, K = 1,2,\ldots,8$$

$$R_{MtT}(0.95;r_i) = R_{MtT}(0.95;S_i) \times r_i \qquad \forall\ i = 1,4,6,9,10,12$$

$$R_{MtT}(0.95;S_i) = \sum_j R_{MtT}(0.95;S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)*} \qquad \forall\ i = 1,4,6,9,10,12$$

$$\sum_i \sum_k R_{VaR}(0.95;r_i)_k + d1^{-} - d1^{+} = 3336273 \qquad i = 1,4,6,9,10,12$$

$$\sum_j WM_j \times PV_j(0) + d2^{-} - d2^{+} = 0.658 \qquad \forall\ j = 1,2,\ldots,14$$

$$\sum_i R_{MtT}(0.95;r_i) + d3^{-} - d3^{+} = 815653 \qquad i = 1,4,6,9,10,12$$

$$r_{\min} \times B_i \le r_i \le r_{\max} \times B_i \qquad \forall\ i = 1,4,6,9,10,12$$

$$2 \le \sum_i B_i \le 3 \qquad i = 1,4,6,9,10,12$$

$$\sum_i r_i = 1 \qquad i = 1,4,6,9,10,12$$

$$B_i = 0 \ or\ 1 \qquad \forall\, i = 1,4,6,9,10,12$$

Note: Here the objectives are scaled using their ideal value

Appendix F is the LINGO code for this model. A sets $W1 = 0.2$, $W2 = 0.5$, and $W3 = 0.3$. After solving the model, A finds that the best portfolio is consist of suppliers 9 and 12, and their weights are 0.8 and 0.2.

**Preemptive Goal Programming Model**

A has three goals in the following priority order:

1. limit the supply portfolio's total VaR-type risk to $3,4000,000
2. supplier portfolio's current strategic value reaches at least 0.615
3. limit the supply portfolio's total MtT-type risk to $900,000

Following is the preemptive goal programming model:

$$Min \quad Z = P_1 \times d_1^+ + P_2 \times d_2^- + P_3 \times d_3^+$$

subject to:

$$PV_j(0) = \sum_i r_i \times V_{(i,j)}(0) \qquad \forall\ j = 1, 2, ..., 14$$

$$R_{VaR}(0.95; r_i)_k = R_{VaR}(0.95; S_i)_k \times r_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12 \,\&\, K = 1, 2, ..., 8$$

$$R_{MtT}(0.95; r_i) = R_{MtT}(0.95; S_i) \times r_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$R_{MtT}(0.95; S_i) = \sum_j R_{MtT}(0.95; S_i)_j \times \frac{R_{MtT}(S_i)_{Total}}{R_{MtT}(S_i)*} \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$\sum_i \sum_k R_{VaR}(0.95; r_i)_k + d1^- - d1^+ = 3336273 \qquad i = 1, 4, 6, 9, 10, 12$$

$$\sum_j WM_j \times PV_j(0) + d2^- - d2^+ = 0.658 \qquad \forall\ j = 1, 2, ..., 14$$

$$\sum_i R_{MtT}(0.95; r_i) + d3^- - d3^+ = 815653 \qquad i = 1, 4, 6, 9, 10, 12$$

$$r_{\min} \times B_i \le r_i \le r_{\max} \times B_i \qquad \forall\ i = 1, 4, 6, 9, 10, 12$$

$$2 \le \sum_i B_i \le 3 \qquad i = 1, 4, 6, 9, 10, 12$$

$$\sum_i r_i = 1 \qquad i = 1, 4, 6, 9, 10, 12$$

$$B_i = 0 \ or\ 1 \qquad \forall\, i = 1, 4, 6, 9, 10, 12$$

From sub model I for the fuzzy goal programming model, A knows that the best $VaR$ value it can get is \$3,336,273, which is less than \$3,4000,000. This means that goal 1 is achievable. Then, A adds the constraint

$$\sum_i \sum_k R_{VaR}(0.95; r_i)_k <= 3400000$$

to the model to try to find the best value for goal 2. Appendix G is the Lingo code for it. It turns out that the best value A can get for goal 2 is 0.618, which is larger than 0.615. Then goal 2 is satisfied. Then, A adds the constrains

$$\sum_j WM_j \times PV_j(0) >= 0.615$$

to the model and it turns out the best value for goal 3 is \$939,932. Even though it is larger than the target value, it is the best A can achieve. This preemptive goal programming model suggests that the supply portfolio should have candidates 9 and 12, and their weights are 0.625 and 0.375.

**Step 5**

After finishing step 4, A has in total the following three solutions available.

1 Candidates 9 and 12 with weights 0.741 and 0.159

Strategic value: 0.594; VaR-type risk value: $3,485,814; MtT-type risk value $879,674

2 Candidates 9 and 12 with weights 0.8 and 0.2

Strategic value: 0.598; VaR-type risk value: $3,336,273; MtT-type risk value $888,399

3 Candidates 9 and 12 with weights 0.625 and 0.375

Strategic value: 0.615; VaR-type risk value: $3,389,428; MtT-type risk value $939,932

Since selecting the right strategic suppliers is critical for A's future success, A arranged a meeting and all the 20 related senior managers attended the meeting. A voting method using majority rule was used in the meeting. Since the number of voters was even, A set up a series of tie-breaking rules before the meeting. In the first round of voting, 8 managers voted for choice 2, 9 voted for choice 3, and 3 voted for choice 1. Obviously, choice 1 was eliminated with the least number of votes. In the second rounding of voting, 10 managers voted for choice 2 and 10 voted for choice 3, and therefore, there was a tie. Fortunately, A already had an appropriate tie-breaking rule ready for this case and it is as follows:

> If alternatives $A_1, A_2, ..., A_K$ receive the same number of votes in round $n$ and one of them has to be eliminated, then the one which received the least number of votes in round $n-1$ should be eliminated. If there is also a tie in round $n-1$, the one also tied in round $n-1$ which received the least number of votes in round $n-2$ should be eliminated, and this continues until back to round 1 if necessary. In the extreme case that the tie is from round 1, other tie-breaking rules should be applied.

Therefore, choice 3 is the winner. The final decision is that candidate 9 and candidate 12 should be chosen, and their weights are 0.625 and 0.375.

# Chapter 6

# MTOM Model for Decision Making Considering Risk at the Operational Level

A mathematical optimization model called Many-to-Many (MTOM) for decision making considering risk at the operational level is presented in this chapter. The basic MTOM model is developed as part of the author's master's thesis. MTOM has a standardized structure to optimize inventory, transportation, and production simultaneously in supply chains. It can handle nondeterministic demands as well as multiple products, components, material types, and transportation options. Due to the standardized structure, MTOM also has the flexibility to be extended to support decision making in short-term supplier selection, risk mitigation, etc.

## 6.1. MTOM Network

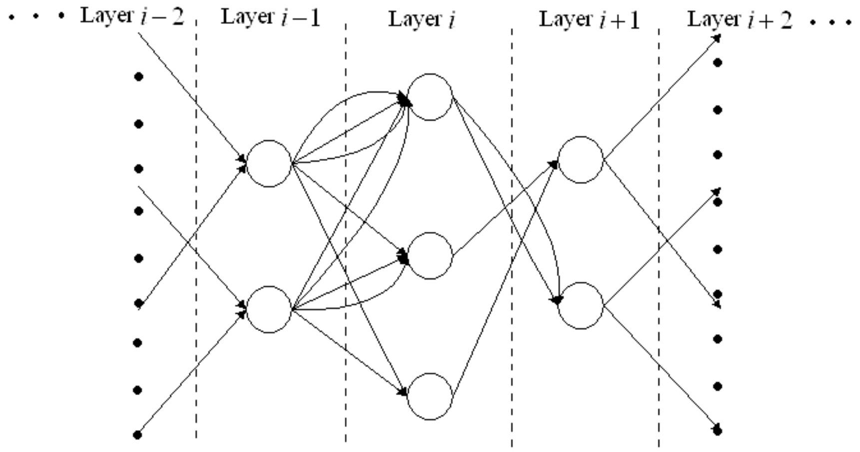


**Figure 6.1 Structure of the MTOM network**

As shown in Figure 6.1, the MTOM network has two types of basic elements: nodes and arcs. Both of them have two sub types: real and virtual. Real nodes denote the locations where Material/Component/Product (M/C/P) can physically stay in supply chains such as warehouses, buffers between different production lines, etc. Real arcs denote processes in the network, which could be transportation or production. Virtual nodes and arcs are used to transform real world supply chain networks into MTOM networks with a standardized structure.

Following are some definitions in the MTOM network:

- Route

  Route consists of continuous arcs. Route can only have one direction. If a route consists of $n$ continuous arcs, its length is $n$.

- Parent

  If A is B's parent, there is an arc connecting A and B and the direction is from A to B.

- Son

  If A is B's parent, B is A's son.

- Layer

  Layer consists of nodes. Between any two nodes in the same layer, there is no route. All parents of the nodes in layer $i$ belong to layer $i-1$. All sons of the nodes in layer $i$ belong to layer $i+1$.

### 6.2. Transformation

In order to build mathematical optimization models based on an MTOM network to optimize inventory, transportation, and production simultaneously considering risk, the supply chains in the real world need first to be described by an MTOM network. Therefore, some transformations may be required.

In an MTOM network, inventory cost only happens at nodes because the in-transit inventory cost can be treated as part of the transportation cost. Production can be expressed by arcs as can transportation. Production cost can also be treated as transportation cost which consists of a certain amount of fixed cost and unit cost. The time consumed by production can be deemed the same as the lead-time of transportation.

The transformation of real world supply chain networks to an MTOM network begins with production processes because they can bring structure changes to the network. If the processed M/C/Ps stay in the same place after finishing, a virtual node and a virtual arc need to be added to the MTOM network. The virtual node denotes the same physical location as the original node where the production occurred. It is added to the MTOM network transform the production process to a regular transportation process. If the processed M/C/Ps do not stay in the same place after finishing, it can be directly treated as a transportation process. Figure 6.2 shows both cases. The basic idea is to transform the production-transportation-inventory networks into traditional transportation-inventory networks with standardized structure.

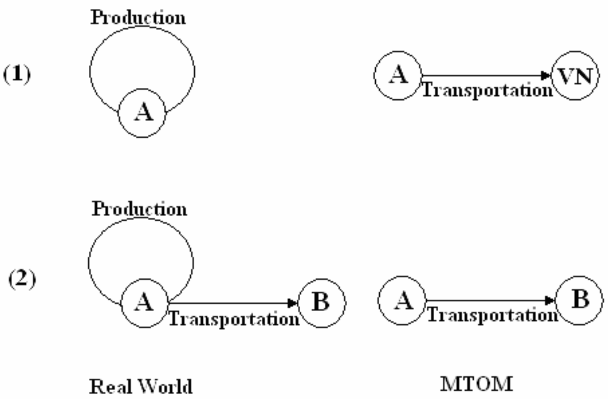


**Figure 6.2 Transforming production process into transportation process**

After transforming all the production processes to transportation processes, the following steps can be followed to change a regular unorganized network into an MTOM network with standardized structure.

Step 1. Find the longest continuous route (it has the maximal number of arcs) in the network. The number of the arcs in this route ($n$) determines the number of layers in the MTOM network.

Step 2. Based on the longest distance (number of arcs) from the starting node(s), put other nodes into different layers until all the nodes are assigned.

Step 3. If two connected nodes in the real network belong to nonconsecutive layers in the MTOM network, virtual arcs and nodes need to be added to connect them. The original arc becomes the last arc in the route which connects these two nodes in the MTOM network.

## Example 1

Manufacturer A has three distribution centers B, C, and D. Product $p$ is produced in A and then shipped to B, C, and D. All possible shipment routes are shown in Figure 6.3 with pointers standing for the directions of shipments.

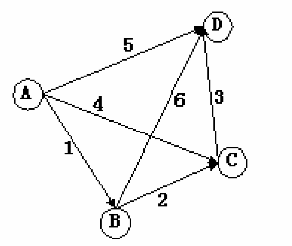


**Figure 6.3 The transportation network in Example 1**

The transportation network shown in Figure 6.3 can be transformed into an MTOM network by the following three steps:

Step 1. The longest continuous route is A → B → C → D, which has 3 arcs. Therefore, the corresponding MTOM network has 4 layers.

Step 2. Since all four nodes are already assigned to different layers, no other nodes need to be assigned.

Step 3. Since A and C are directly connected in the real world network, but not directly connected in the MTOM network, virtual node $VN_3$ and virtual arc $VL_3$ are added to connect them. Similarly, B and D need $VN_4$ and $VL_4$ to be connected. Two virtual nodes ($VN_1$ and $VN_2$) and two virtual arcs ($VL_1$ and $VL_2$) are needed in the MTOM network to connect A and D since there are two layers between them.

The finished MTOM network is shown in Figure 6.4.

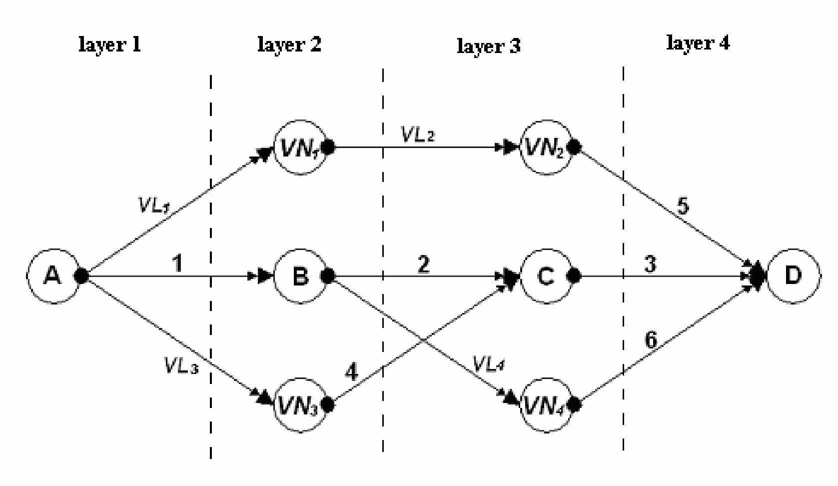


**Figure 6.4 MTOM network for Example 1**

## Example 2

As shown in Figure 6.5, A is a supplier. Components for product $p$ are manufactured in A. Finished components can either stay in A or be immediately shipped to assembly centers B and C. From A to B, there are three different transportation modes. From A to C, there is only one transportation mode. When assembly is done in B, finished product $p$ can be directly shipped to distribution centers G and H. From B to G, there is only one transportation mode, and there are two transportation modes from B to H. Finished product $p$ can also be shipped to warehouse E at first, and then E supplies H. There is only one transportation mode from B to E and E to H. Finished products in C can be shipped to warehouses D and F. From C to D, there is only one transportation mode. From C to F, there are two transportation modes. D supplies H and F supplies G. There is only one transportation mode from D to H and F to G.

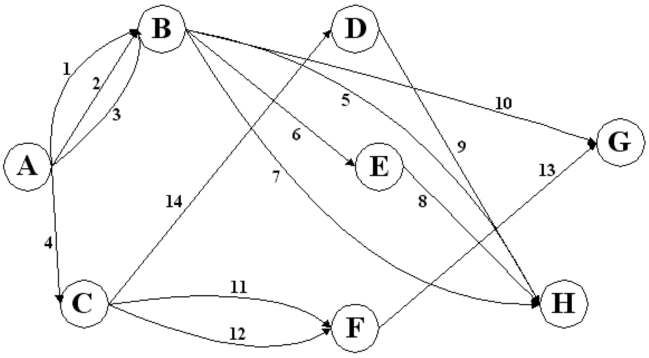


**Figure 6.5 Network in Example 2**

The network shown in Figure 6.5 can be transformed into an MTOM network as shown in Figure 6.6.

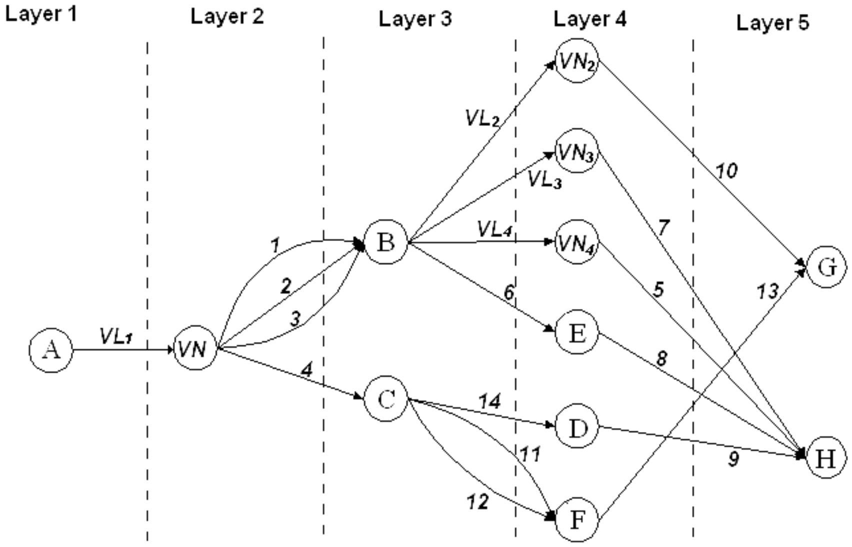


**Figure 6.6 MTOM network for Example 2**

## 6.3. Mathematical model for MTOM network

### Index

| | |
|---|---|
| $i$ | Number of layers in the network, $i = 1, 2, 3, \ldots$ |
| $j_i$ | Number of nodes in layer $i$, $j = 1, 2, 3, \ldots$ |
| $l_{(i,j_1,j_2)}$ | Number of arcs from node $j_1$ in layer $i-1$ to node $j_2$ in $i$ |
| $k$ | ID of M/C/P, $k = 1, 2, 3, \ldots$ |
| $t$ | Time period, $t = 1, 2, 3, \ldots$ |
| $s$ | Number of capacity constraints associated with nodes and arcs, $s = 1, 2, 3, \ldots$ (e.g. $s$=1 can denote weight constraint, $s$=2 can denote size constraint, etc.) |
| $r$ | Number of different VaR-type risks from suppliers |
| $m$ | Number of different MtT-type risks from suppliers |
| $q$ | Number of suppliers in the network |

### Network parameters

- Arc related:

| | |
|---|---|
| $LFC\,(i, j_1, j_2, l)$ | Fixed transportation/production cost associated with arc $l$ if it is used at time $t$. $l$ is from node $j_1$ in layer $i-1$ to node $j_2$ in layer $i$ |
| $LUC\,(i, j_1, j_2, l, k)$ | Unit transportation/production cost of M/C/P $k$ associated with arc $l$, which is from node $j_1$ in layer $i-1$ to node $j_2$ in layer $i$ |
| $LC_s(i, j_1, j_2, l)$ | Transportation/production capacity limit $s$ associated with arc $l$, which is from node $j_1$ in layer $i-1$ to node $j_2$ in layer $i$ |

| | |
|---|---|
| $LL(i, j_1, j_2, l)$ | Transportation /production lead-time associated with arc $l$, which is from node $j_1$ in layer $i$ to node $j_2$ in layer $i+1$ |

- Node related:

| | |
|---|---|
| $NFC(i, j)$ | Fixed cost if node $j$ in layer $i$ is used at time $t$ |
| $NUC(i, j, k)$ | Unit inventory cost of M/C/P $k$ at node $j$ in layer $i$ per time unit |
| $NC_s(i, j)$ | Capacity limit $s$ at node $j$ in layer $i$ |
| $CNUD(i, j, k, t)$ | Unit lost sale cost of M/C/P $k$ due to underestimating demand |
| $CNOS(i, j, k, t)$ | Unit overstock cost of M/C/P $k$ due to overestimating demand |

- Material related:

| | |
|---|---|
| $MC_s(k)$ | Character of M/C/P $k$ associated with constraint $s$ |
| $UC(k)$ | Unit price of M/C/P $k$ |

- Demands

| | |
|---|---|
| $f(x; i, j, k, t)$ | Demand probability function for M/C/P $k$ at node $j$ in layer $i$ at time $t$; i.e. the probability that the demand for M/C/P $k$ at node $j$ in layer $i$ at time $t$ is less than $x$ equals $\int_0^x f(x; i, j, k, t)dx$ |

- Risk related

| | |
|---|---|
| $R_{VaR}(\alpha;V_q)_r$ | VaR-type supply risk $v$ from supplier $q$ at confidence level $\alpha$ when the order value is $V_q$ |
| $R_{MtT}(\alpha;V_q)_m$ | MtT-type supply risk $m$ from supplier $q$ at confidence level $\alpha$ when the order value is $V_q$ |

**Decision variables**

- Arc related:

| | |
|---|---|
| $LD(i,j_1,j_2,l,t)$ | Binary variable. If arc $l$ from node $j_1$ in layer $i-1$ to node $j_2$ in layer $i$ is used at time $t$, $LD(i,j_1,j_2,l,t)$ equals 1; it equals 0 otherwise |

- Node Related:

| | |
|---|---|
| $ND(i,j,t)$ | Binary variable. If node $j$ in layer $i$ is used at time $t$, $ND(i,j,t)$ equals 1; it equals 0 otherwise |
| $XO(i,j_1,j_2,l,k,t)$ | The quantity of M/C/P $k$ enter arc $l$ at time $t$, which is from node $j_1$ in layer $i$ to node $j_2$ in layer $i+1$ |
| $XI(i,j_1,j_2,l,k,t)$ | The quantity of M/C/P $k$ received through arc $l$ at time $t$, which is from node $j_1$ in layer $i-1$ to $j_2$ in layer $i$ |
| $NI(i,j,k,t)$ | Inventory level of M/C/P $k$ at node $j$ in layer $i$ at time $t$ |
| $AD(i,j,k,t)$ | The demand of M/C/P $k$ at node $j$ in layer $i$ at time $t$ that the supply chain is prepared to satisfy |

- Node Related:

| | |
|---|---|
| $V_q$ | Total order value with supplier $q$ |

**Constraints**

- Arc related:

▪ flow-in equals flow-out

$$M \times \left| XO(i, j_1, j_2, l, t) \right| = \left| XI(i+1, j_1, j_2, l, t + LL(i, j_1, j_2, l)) \right| \quad \forall i, j_1, j_2, l, t$$

where $\left| XO(i, j_1, j_2, l, t) \right| = \begin{bmatrix} XO(i, j_1, j_2, l, k_1, t) \\ XO(i, j_1, j_2, l, k_2, t) \\ XO(i, j_1, j_2, l, k_3, t) \\ \vdots \\ XO(i, j_1, j_2, l, k_m, t) \end{bmatrix}'$ is a vector, which has $m$ elements. $\left| XO(i, j_1, j_2, l, t) \right|$ can be called ***incoming M/C/P list*** to arc $l$, which is from node $j_1$ in layer $i$ to node $j_2$ in layer $i+1$. $XO(i, j_1, j_2, l, k_1, t)$, $XO(i, j_1, j_2, l, k_2, t)$, …… are the quantities of M/C/P $K_1$, $K_2$, ……. Similarly, $\left| XI(i, j_1, j_2, l, t) \right|$ can be called ***outgoing M/C/P list*** to arc $l$. $M$ is called the manufacturing/transportation matrix, which will be introduced later.

▪ Capacity constraints

Outgoing M/C/P list is used to check the transportation and production capacity constraints.

$$\sum_k MC_s(k) \times XI(i, j_1, j_2, l, k, t) \le LC_s(i, j_1, j_2, l) \times LD(i, j_1, j_2, l, t)$$

$$\forall i, j_1, j_2, l, t, s$$

- Node related:

▪ Flow-in equals flow-out

To M/C/P $k$ at node $j_2$ in layer $i$, the inventory at the beginning of time period $t+1$ equals the inventory at the beginning of time period $t$ plus the quantities received through all the inward arcs, minus the quantities shipped out throught all the outward arcs including the satisfied demands.

$$NI(i, j_2, k, t+1) = \sum_{j_1} \sum_{l} XI(i, j_1, j_2, l, k, t) + NI(i, j_2, k, t)$$

$$- \sum_{j_3} \sum_{l} XO(i, j_2, j_3, l, k, t) - AD(i, j_2, k, t) \qquad \forall \quad i, j_2, k, t$$

▪ Capacity constraints

$$\sum_{k} MC_s(k) \times NI(i, j, k, t) \le NC_s(i, j) \times ND(i, j, t) \qquad \forall i, j, t, s$$

- Supplier related:

$$V_q = \sum_{i, j_1 \in q} XO(i, j_1, j_2, l, k, t) \times UC(k) \qquad \forall q$$

- Decision variables related:

▪ Non-Negative

$$XO(i, j_1, j_2, l, k, t) \ge 0 \qquad \forall i, j_1, j_2, l, k, t$$

$$XI(i, j_1, j_2, l, k, t) \ge 0 \qquad \forall \quad i, j_1, j_2, l, k, t$$

$$NI(i, j, k, t) \ge 0 \qquad \forall \quad i, j, k, t$$

$$AD(i, j, k, t) \ge 0 \qquad \forall \quad i, j, k, t$$

▪ Binary

$$LD(i, j_1, j_2, l, t) = 0 \; or \; 1 \qquad \forall \quad i, j_1, j_2, l, t$$

$$ND(i, j, t) = 0 \; or \; 1 \qquad \forall \quad i, j, t$$

## Objective Function

- Individual arc cost $C_{IAC}(i, j_1, j_2, l)$

  This represents the cost associated with arc $l$ which is from node $j_1$ in layer $i-1$ to node $j_2$ in layer $i$ over $t$ time periods

  $$C_{IAC}(i, j_1, j_2, l) = \sum_t \sum_k (XI(i, j_1, j_2, l, k, t) \times LUC(i, j_1, j_2, l, k) + LD(i, j_1, j_2, l, t) \times LFC(i, j_1, j_2, l))$$

- Individual node fixed cost and inventory cost $C_{INC}(i, j)$

  This represents the cost associated with node $j$ in layer $i$ over $t$ time periods

  $$C_{INC}(i, j) = \sum_t ND(i, j, t) \times NFC(i, j) + \sum_t \sum_k NUC(i, j, k) \times NI(i, j, k, t)$$

- Expected individual node lost sale cost and overstock cost $C_{LS}(i, j)$

  $$C_{LS}(i, j) = \sum_k \sum_t \begin{pmatrix} \int_0^{AD(i,j,k,t)} f(x; i, j, k, t)(AD(i, j, k, t) - x) \times CNOS(i, j, k, t) dx + \\ \int_{AD(i,j,k,t)}^{\infty} f(x; i, j, k, t)(x - AD(i, j, k, t)) \times CNUD(i, j, k, t) dx \end{pmatrix}$$

- VaR-type risks

  $$R_{VaR}(\alpha, V) = \sum_q \sum_r R_{VaR}(\alpha; V_q)_r$$

- MtT-type risks

  $$R_{MtT}(\alpha; V) = \sum_{q=1}^{Q} R_{VaR}(\alpha; V_q)$$

  $$R_{VaR}(\alpha; V_q) = \sum_{m=1}^{M} \left( R_{MtT}(\alpha; V_q)_m \times \frac{M_{total}}{M^*} \right)$$

  $M_{total}$ and $M^*$ were already introduced in Chapter 4.

Therefore, the **objective functions of the MTOM** network are:

$$Min \quad C_T = \sum_i \sum_{j_1} \sum_{j_2} \sum_l C_{IAC}(i, j_1, j_2, l) + \sum_i \sum_j (C_{INC}(i, j) + C_{LS}(i, j))$$

$$Min \quad R_{VaR}(\alpha; V)$$

$$Min \quad R_{MtT}(\alpha; V)$$

The above model is a typical multi-criteria optimization problem, and some well-adopted methods can be used to solve it such as fuzzy goal programming, non-preemptive goal programming, and preemptive goal programming

### 6.4. M Matrix

$M(i, j_1, j_2, l)$ is the manufacturing/transportation matrix. It is used to handle the quantities and M/C/P ID changes caused by production processes. Different production processes may have different M matrices. Entry $a_{ij}$ in M is decided by the process.

$$M(i, j_1, j_2, l) = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & \cdots & \cdots \\ a_{21} & a_{22} & a_{23} & \cdots & \cdots & \cdots \\ a_{31} & a_{32} & \ddots & \cdots & \cdots & \cdots \\ a_{41} & \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

Suppose that the "incoming M/C/P list" to arc $l$ is $|XO(i, j_1, j_2, l, t)| = \begin{bmatrix} o_1 \\ o_2 \\ o_3 \\ \vdots \\ o_m \end{bmatrix}$, which means that at time $t$, there are $O_1$ units of M/C/P 1, $O_2$ units of M/C/P 2,$\cdots\cdots$, $O_m$ units of M/C/P $m$ shipped out from $j_1$ in layer $i$ to node $j_2$ in layer $i+1$ through arc $l$. Suppose that the "outgoing M/C/P list" to arc $l$ is

$$\left|XI(i+1, j_1, j_2, l, t+LL(i, j_1, j_2, l))\right| = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ \vdots \\ i_m \end{bmatrix}$$

, which means that at time $t+LL(i, j_1, j_2, l)$, there are $i_1$ units of M/C/P 1, $i_2$ units of M/C/P 2, $\cdots\cdots$, $i_m$ units of M/C/P $m$ received at node $j_2$ in layer $i+1$ from node $j_1$ in layer $i$ through arc $l$.

If $i_k = o_k$ is true for every $k$, arc $l$ denotes a transportation process (without any damage during the process). The M matrix associated with arc $l$ is an identity matrix as follows:

$$M(i, j_1, j_2, l) = \begin{bmatrix} 1 & 0 & 0 & \cdots \\ 0 & 1 & 0 & \cdots \\ 0 & 0 & \ddots & 0 \\ \vdots & \vdots & \vdots & 1 \end{bmatrix}$$

If $i_k = o_k$ is not always true for every $k$, arc $l$ is a production process (or a transportation process with ascertained damage). The M matrix associated with arc $l$ is as follows:

$$M(i, j_1, j_2, l) = \begin{bmatrix} \frac{i_1}{n \times o_1} & \frac{i_1}{n \times o_2} & \cdots \\ \frac{o_2}{n \times o_1} & \cdots & \cdots \\ \vdots & \cdots & \ddots \end{bmatrix}$$

where $n$ is the number of different types of M/C/P needed for the production process denoted by arc $l$. Naturally, there are two rules regarding the M matrix:

- If $i_p = 0$, the $p$ th row of the M matrix are all zero
- If $o_p = 0$, the $p$ th column of the M matrix are all zero

## Example 3

Production process A is used to produce product $k_4$ and $k_5$. Five units of $k_1$, four units of $k_2$, and three units of $k_3$ can produce three units of $k_4$ and two units of $k_5$.

Since $o_4 = 0$ and $o_5 = 0$, the 4th and 5th columns of M matrix are all zeros. Since $i_1 = 0$, $i_2 = 0$, and $i_3 = 0$, the 1st, 2nd, and 3rd rows of M matrix are all zeros. Therefore, part of the M is already known.

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ ? & ? & ? & 0 & 0 \\ ? & ? & ? & 0 & 0 \end{bmatrix}$$

The non-zero $a_{ij}$ s are:

$$n = 3$$

$$a_{41} = \frac{i_4}{n \times o_1} = \frac{3}{3 \times 5} = \frac{1}{5} \quad a_{42} = \frac{i_4}{n \times o_2} = \frac{3}{3 \times 4} = \frac{1}{4} \quad a_{43} = \frac{i_4}{n \times o_3} = \frac{3}{3 \times 3} = \frac{1}{3}$$

$$a_{51} = \frac{i_5}{n \times o_1} = \frac{2}{3 \times 5} = \frac{2}{15} \quad a_{52} = \frac{i_5}{n \times o_2} = \frac{2}{3 \times 4} = \frac{1}{6} \quad a_{53} = \frac{i_5}{n \times o_3} = \frac{2}{3 \times 3} = \frac{2}{9}$$

Therefore, the M matrix associated with production process A is:

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1/5 & 1/4 & 1/3 & 0 & 0 \\ 2/15 & 1/6 & 2/9 & 0 & 0 \end{bmatrix}$$

### 6.5. Example

In this section, an example is presented to show how the MTOM model works. Manufacturer C produces two products PI and PII, which require two types of raw materials: RI and RII. There are two suppliers, A and B, which both can supply RI and RII to C. The main retailers of products PI and PII are D and E. Figure 6.7 shows their relationship.

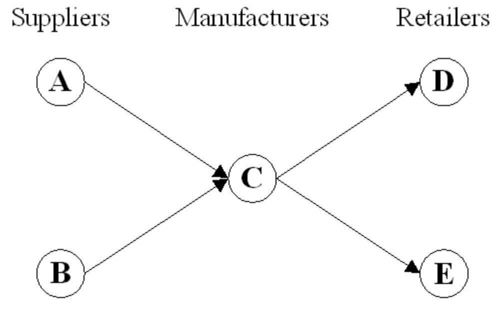


**Figure 6.7 The structure of the supply chain**

3 units of RI and 4 units of RII are required to produce 1 unit of PI. 4 units of RI and 3 units of RII are required to produce 1 unit of PII. Production for PI and PII require one week. Physical size is the only concern of capacity constraint for transportation and inventory. The default time unit in this example is a week, and the default cost unit is the dollar.

Standard size unit is used in Table 6.1, Table 6.4, Table 6.5, and Table 6.6. Table 6.1 shows the unit sizes of RI, RII, PI, and PII in standard unit size.

**Table 6.1 Unit sizes of materials and products**

| | RI | RII | PI | PII |
|---|---|---|---|---|
| Size (in standard size unit) | 1 | 1 | 3 | 3 |

Table 6.2 shows the forecasted demands in the next 8 weeks by retailer D and E. However, there is only a 75% chance that the forecasts are accurate. With a 15% chance, the actual demand will be 10 units more, and a 10% chance that the actual demand will be 15 units less. PI and PII need to be prepared before they can be sold to customer in D and E. Therefore, if the prepared quantity is less than the real demand, lost sale cost will be incurred. If the prepared quantity is more than the real demand, overstock cost will be incurred. Table 6.3 shows the lost sale costs and the overstock costs in D and E.

**Table 6.2 Demand forecasts in the next 8 weeks**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Demand for PI in D | 200 | 180 | 220 | 320 | 140 | 260 | 200 | 180 |
| Demand for PII in D | 120 | 220 | 160 | 190 | 250 | 220 | 120 | 200 |
| Demand for PI in E | 110 | 230 | 170 | 180 | 240 | 220 | 110 | 180 |
| Demand for PII in E | 210 | 170 | 230 | 310 | 150 | 250 | 210 | 260 |

**Table 6.3 Lost sale costs and overstock costs in D and E**

| | Lost Sale Cost (per unit) | | Overstock Cost (per unit) | |
|---|---|---|---|---|
| | PI | PII | PI | PII |
| D | 15 | 18 | 8 | 6 |
| E | 20 | 22 | 6 | 8 |

RI and RII can be shipped from suppliers A and B to manufacturer C directly. There are two transportation modes from A to C and B to C. Table 6.4 shows the detailed information. (SCU denotes the shipping cost per standard size unit)

**Table 6.4 Shipping information from A and B to C**

| Route | Mode | Fixed Cost | SCU | Capacity Constraint | Lead-time |
|---|---|---|---|---|---|
| A to C | I | 500 | 3 | 2500 | 1 |
| | II | 1000 | 2 | 4000 | 1 |
| B to C | I | 1500 | 2 | 2500 | 1 |
| | II | 2500 | 1 | 5000 | 2 |

A charges C \$1.20 for each unit of RI and \$1.50 for each unit of RII. B charges C \$1.00 for each unit of RI and \$1.30 for each unit of RII. C summarizes the VaR-type risks with A and B into 3 categories and the estimated VaR values expressed in dollars have the following relationship with the total order value V at confidence level 95%.

**Category 1:**

A: $VaR_1(0.95,V) = 3.13V + 7234.12$  B: $VaR_1(0.95,V) = 2.92V + 8235.72$

**Category 2:**

A: $VaR_2(0.95,V) = 5.3V$  B: $VaR_2(0.95,V) = 3.7V + 3451.23$

**Category 3:**

A: $VaR_3(0.95,V) = 4.7V + 121$  B: $VaR_3(0.95,V) = 4.6V$

Two types of MtT-type risks from A and B concern C: production delay and defective materials. If either problem occurs, C cannot make the production goals for lack of materials. C does have an emergency backup supplier K available to get any quantity of RI and RII promptly. However, K charges $20 for each unit of RI or RII with shipping cost included. Since both MtT-type risks have the same result, C combined both MtT-type risks together and made the following summaries based on its formal experience with A and B.

- The probability that A can fulfill orders with the right quantities and 0 defective rate is 95%. A has a 2% chances to fulfill 99% of the order, a 2% chances to fulfill 98% of the order, and a 1% chances to fulfill only 95% of the order.
- The probability that B can fulfill orders with the right quantities and 0 defective rate is 90%. A has a 4% chances to fulfill 99% of the order, a 3% chances to fulfill 98% of the order, and a 3% chances to fulfill only 95% of the order.

Finished PI and PII can be directly shipped from C to D and E. There is only one transportation mode from C to D and E. C is responsible for all the transportation costs in the network, and C also manages the inventories in D and E. Table 6.5 shows the detailed information.

**Table 6.5 Shipping information from C to D and E**

| Route | Fixed Cost | SCU | Capacity Constraint | Lead-time |
|---|---|---|---|---|
| C to D | 1000 | 2 | 5800 | 1 |
| C to E | 800 | 2 | 4500 | 1 |

Shipping Cost = Fixed Cost + Overall Shipment Size × SCU.

Finished products can also be stored in the warehouses of C, D, and E. Detailed information is shown in Table 6.6.

**Table 6.6 Unit inventory cost per week**

| | Unit inventory cost per week for PI | Unit inventory cost per week for PII | Capacity |
|---|---|---|---|
| C | 2 | 2 | 4000 |
| D | 4 | 3 | 4500 |
| E | 3 | 4 | 5000 |

Company C has two separate production lines to manufacture PI and PII. Table 6.7 shows the production capacities, unit production costs, and fixed costs.

**Table 6.7 Information about production lines in C**

| | Operation Cost | Unit Production Cost | Weekly Production Capacity |
|---|---|---|---|
| C I | 600 | 3 | 650 |
| C II | 500 | 3 | 600 |

Production Cost = Fixed Operation Cost + Product Quantity × Unit Production Cost.

Based on the predicted demands for the next 8 weeks, C must make decisions in production, transportation and inventory. The overall objectives are to minimize total cost including production, transportation, and inventory costs as well as the VaR- and MtT-type risks from A and B. Assume that at the beginning of week one, there are no materials or products in any arcs. Initial inventories in C, D, and E are shown in Table 6.8.

**Table 6.8 Initial inventory in C, D, and E**

| | C | D | E |
|---|---|---|---|
| PI | 520 | 550 | 550 |
| PII | 500 | 400 | 400 |

The MTOM network for this example is shown in figure 6.8.

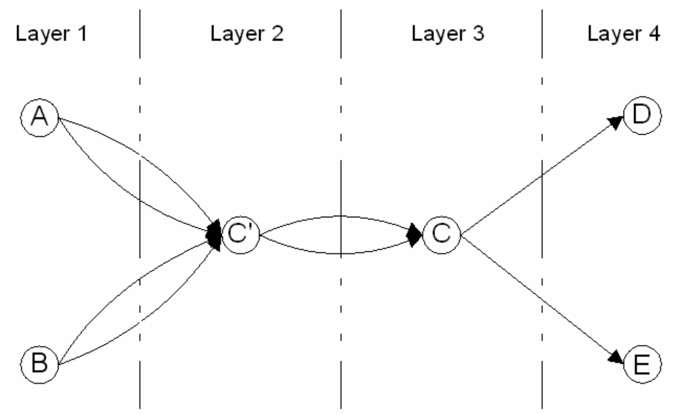


**Figure 6.8 The corresponding MTOM network**

In summary, this is a multi-criteria production, transportation, and inventory optimization problem with multiple materials/products, multiple companies, and multiple transportation modes considering risks. C decides to solve this multi-criteria optimization problem by using the preemptive goal programming model. The detailed steps are:

1. Minimize the total cost first. Let $C_{\min}$ stand for the minimum possible total cost.
2. Set $1.05C_{\min}$ as the upper limit for the total cost and then minimize the total MtT-type risk. Let $R_{MtT}$ stand for the minimum possible MtT-type risk.
3. Set $1.05R_{MtT}$ as the upper limit for total MtT-type risk and then minimize the total VaR-type risk. The solution is the final decision.

LINGO is used to generate the MTOM model for this problem and solve it. Appendix I shows the LINGO code for Step 3. Detailed descriptions and definitions can be found in the code. Table 6.9, Table 6.10, and Table 6.11 show the final solution given by LINGO.

**Table 6.9 Optimal transportation solution from A and B to C**

| | Shipping quantity of RI | | | | Shipping quantity of RII | | | |
|---|---|---|---|---|---|---|---|---|
| | Mode I | | Mode II | | Mode I | | Mode II | |
| | A→C | B→C | A→C | B→C | A→C | B→C | A→C | B→C |
| Week 1 | 0 | 0 | 1198 | 0 | 0 | 0 | 899 | 2500 |
| Week 2 | 0 | 0 | 2946 | 0 | 0 | 0 | 495 | 2500 |
| Week 3 | 0 | 0 | 3034 | 0 | 0 | 0 | 483 | 2500 |
| Week 4 | 0 | 0 | 2855 | 68 | 0 | 0 | 572 | 1380 |
| Week 5 | 0 | 0 | 1772 | 0 | 0 | 0 | 0 | 0 |
| Week 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Week 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Week 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 6.10 Optimal transportation solution from C to D and E**

| | Shipping quantity of PI | | Shipping quantity of PII | |
|---|---|---|---|---|
| | C to D | C to E | C to D | C to E |
| Week 1 | 0 | 0 | 0 | 0 |
| Week 2 | 355 | 0 | 280 | 210 |
| Week 3 | 0 | 140 | 0 | 310 |
| Week 4 | 125 | 225 | 250 | 150 |
| Week 5 | 245 | 205 | 205 | 250 |
| Week 6 | 185 | 95 | 105 | 210 |
| Week 7 | 165 | 165 | 200 | 260 |
| Week 8 | 0 | 0 | 0 | 0 |

**Table 6.11 Optimal production schedule in C**

| | Production quantity of CI | Production quantity of CII |
|---|---|---|
| Week 1 | 0 | 0 |
| Week 2 | 0 | 300 |
| Week 3 | 449 | 400 |
| Week 4 | 405 | 455 |
| Week 5 | 532 | 315 |
| Week 6 | 0 | 460 |
| Week 7 | 0 | 0 |
| Week 8 | 0 | 0 |

The total cost for this supply chain in the next 8 weeks is \$177,842. The total MtT-type risk is \$761, and the total VaR-type risk is \$383,558.

# Chapter 7

# Conclusions and Recommendations for Future Research

## 7.1. Achievement of research goals

As stated in Chapter 1, the primary questions this research is trying to answer are:

- How to quantify supply risks?
- How to support decision-making regarding suppliers considering risks at both the strategic and operational levels?

In order to answer the above two questions, this thesis mainly completed the following research tasks.

- Developed a mathematical model to quantify supply risks and developed several measures for supply risks

  In Chapter 4, supply risks are classified into two categories based on their characteristics for quantification purposes: VaR type and MtT type. Since data are essential for risk quantification, strategies based on different data availabilities are discussed. According to the general definition of risk, detailed risk functions are developed for each type. For VaR-type risks, generalized extreme value (GEV) distribution is recommended for the hazard function. The probability weighted moments method can be used to estimate the parameters, and either the Sherman test or Kolmogorov-Smirnov statistics can be used for the fitness test. Poisson distribution is recommended for the exposure function for its special properties. An example is given to show how to combine these two components of risk together to get the final VaR-type risk distribution table. The MtT type is further classified into three sub-types: S-type, N-type, and L-type. Corresponding detailed hazard functions are given by referring to Toguchi's loss function. Gamma distribution is recommended for S-type exposure function, generalized hyperbolic distribution is recommended for N-type exposure function, and Beta distribution is recommended for L-type exposure function. The detailed S-type, N-type, and L-type risk functions are given thereafter. An example is presented as well for MtT type. After detailed risk functions are developed, four risk measures are suggested: R(α) which is the risk at confidence level α; PLe(R) which is the possibility of risk value less than R; PLa (R) which is the possibility of risk value larger than R; and E which is the expected loss caused by a certain risk. Since firms usually have more than one supplier and there are different risks associated with each supplier, in the last section of Chapter 4, the following topics are discussed: how to combine different VaR-type or MtT-type risks from same supplier; how to combine the same VaR-type or MtT-type risks from different suppliers; and how to combine total VaR-type or MtT-type risks from different suppliers.

- Developed a multi-criteria method to support decision-making in supplier selection at the strategic level, considering risks

  In Chapter 5, a multi-criteria strategic supplier selection method is developed. The first step is to identify the factors that need to be considered for supplier selection hierarchically. Instead of ascertained weights, weight ranges are used to overcome the shortcomings of traditional criteria weighting methods. The calculation method for weight ranges is introduced as well. The second step is to use collected data including candidate suppliers' performance on each criterion to calculate the strategic value of each supplier on each criterion which considers the possible future performance of candidate suppliers instead of their past performance. It is the future performance that matters to buyers. The third step is to reduce the candidate list to a desirable length by using the Fuzzy Weighted Best Ranking model. The basic idea is similar to data envelopment analysis: the exact weight of each criterion is chosen for each supplier within the weight range that will make the candidate look the best. The fourth step is for buyers to use different multi-criteria optimization problem solving methods they prefer to find out the best compromised solutions for the proposed multi-criteria supplier selection problem. Usually, the results from using different methods are different. Since there is no way to guarantee which method gives the best solution, senior managers' years of experience should be fully utilized. Thus the last step is to let senior managers choose the best one among the solutions from step 4. Many methods can be used in such a multiple decision-makers case to choose the winner such as AHP, Delphi method, Borda count, and voting using majority rule. Again, an example is given to show all the steps.

- Developed an optimization model to support decision-making at the operational level for order quantities, shipment options, production scheduling, etc., considering risks

  The basic MTOM model is developed in the author's Master's thesis as one of the basic part for this Ph.D. thesis. Due to its standardized structure, the MTOM model can optimize production, transportation, and inventory simultaneously. It can handle multiple products, companies, and transportation modes, and it supports dynamic formation of temporary supply chain and member selection. Chapter 6 first introduces the network structure of MTOM. Then, the method of transforming real world supply chain networks into MTOM networks is given as are examples. The mathematical model of MTOM is shown thereafter. The expanded MTOM model now can handle unascertained demands. After adding MtT-type risk measure $R_{MtT}$ and VaR-type risk measure $R_{VaR}$ into the model, MTOM becomes a multi-criteria optimization model with three objectives: minimizing total supply chain cost, minimizing total VaR-type supply risk, and minimizing total MtT-type supply risk. An example is given to show all the steps of the MTOM model in the last section of Chapter 6.

In addition to finishing the above research tasks, Chapter 3 discusses several important topics related to supply risk management and a new risk classification method is proposed. The major contributions of this research as proposed in Chapter 1 are:

1. An elaborate but comprehensive risk classification method
2. A supply risk quantification method
3. Several measures for supply risks

4. A multi-criteria method for firms to select strategic suppliers considering supply risks
5. A multi-criteria optimization model for firms to make decisions at the operational level considering supply risks

## 7.2. Future research opportunities

Risk management in supply chain is a relatively new topic and very limited quantitative research has been done so far. Although the research in this thesis has made some contributions in this new research area, much more work needs to be done. Following are some major research opportunities in this area that can be accomplished by continuing the finished research in this thesis.

### 1. A quantitative risk prioritizing method

So far, all the risk classification and prioritizing methods in supply chain are qualitative in nature, including the new one developed in Chapter 3. Although these methods can give decision-makers some rough ideas about which risks should be mitigated first, second, etc., they cannot offer detailed enough information such as which risk has a higher priority than the others in the same qualitative priority category and quantitatively what the priorities are. Firms need quantitative information to decide how to allocate their limited resources for each risk. Therefore, methods should be developed to prioritize supply risk quantitatively. Obviously, multiple aspects of each risk should be considered for prioritizing including severity, frequency, cost/benefit ratio, etc. The risk quantification method developed in Chapter 4 can be used as the basis for these quantitative prioritizing methods.

### 2. New risk mitigation methods and tools

As a new focus in supply chain management, currently available risk mitigation methods and tools are limited. New methods and tools need to be developed to meet the various needs of firms. For example, insurance derivatives in the financial market can be used. A firm can issue a special bond with a higher than normal interest rate. If nothing happens, bond investors can enjoy the higher than normal interest rate. If disruptions occur in the supply chain and cause losses, the interest or even the principle will be used to cover the losses as part of the bond contract. The advantages to firms are the extra available funds and the knowledge of what the costs for risk mitigation will be.

### 3. Identify better-fitted distributions for each risk type as well as some experienced parameter values

Although this research offers some suggestions about the distributions for different types of hazard and exposure functions, they may not always be the best choices. After applying them in the real world, firms may find better distributions for their own cases. Some experienced values may be found for certain parameters.

### 4. How to manage other risks in supply chain quantitatively

Besides supply risks, there are many other risks existing in a supply chain such as the risks from retailers, risks from 3PL providers, risks from customer service contractors, etc. Those risks must be managed quantitatively as well. Considering the similarities of those risks with supply risks, this research can be extended to manage them. Retailers can be deemed as a special type of supplier which offers “selling service.” 3PL providers are the suppliers offering “transportation service.”

Although the importance of risk management in a supply chain has already been widely realized by industries and researchers, more work needs to be done to understand it correctly. For example, in a corporation, proposing to spend more to mitigate risks, including supply risks, may cause some controversy. The stockholders should already have their risks hedged by having an appropriate portfolio. Therefore, it may not be in the best interest of stockholders to pay extra money to hedge risks again. The other dilemma is whether a firm should hedge risks if their competitors do not hedge. Competitive pressures in most industries are very intensive. Adding costs to mitigate supply chain risks can lower the firm’s profit margins and thus put the firm at a disadvantaged in the competitive market if no disruptions occur. In other words, firms may be forced to bet their luck by their competitors. Another issue is the top-level managers’ attitude towards risk management. Risk managers and procurement managers in a firm may have difficulty explaining to higher-level managers why they spent money for “nothing” if no disruptions occurred although they will be appreciated if disruptions do occur. The interesting part is that if they really did a good job of risk mitigation and prevented the disruptions from happening, they may actually put themselves into a position in which they have difficulty explaining what the extra “cost” is for.

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# Appendix A

## Lingo code for the FWBR model in chapter 5

```
model:

sets:
supplier/1..15/:VT,B,P,N;
criterion/1..14/:WL,WU,WR;
s_value(supplier,criterion):V;
endsets

!******************************************************************************;
!WL: the lower bound of weight range;
!WU: the upper bound of weight range;
!WR: the weights that can make the supplier s achieve the best ranking;
!VT: the total strategic value that supplier i has when the weight are wr;
!V: the currant strategic value of supplier i regarding criterion j;
!B: binary varible assigned to each potential supplier;
!******************************************************************************;
@FOR(criterion(j):WR(j)>=WL(j));
@FOR(criterion(j):WR(j)<=WU(j));
@SUM(criterion(j): WR(j))=1;
@FOR(supplier(i):VT(i)=@SUM(criterion(j):WR(j)*V(i,j)));
@FOR(supplier(i)|i#NE#s:VT(i)-VT(s)=P(i)-N(i));
@FOR(supplier(i)|i#NE#s:B(i)*M>=P(i));
@FOR(supplier(i):@BIN(B(i)));
SS=@SUM(supplier(i)|i#NE#s:B(i));
!******************************************************************************;
min = SS;

data:
M=1000;
s=1;
WL = 0.109, 0.021, 0.030, 0.022, 0.004, 0.012, 0.127, 0.049, 0.203, 0.047, 0.016, 0.016, 0.019,
0.012;
WU = 0.227, 0.045, 0.069, 0.045, 0.008, 0.026, 0.219, 0.102, 0.387, 0.159, 0.035, 0.035, 0.033,
0.023;
V= 0.499,0.922,0.148,0.015,0.626,0.225,1,0.407,0.76,0.067,0.8,0.263,0.36,0.298,
    0.27,0.658,0.398,0.014,0.582,1,0.561,0.864,0.307,0.13,0.248,0.365,0.098,0.327,
    0.421,1,0.034,0.019,0.976,0.356,0.007,0.956,0.525,0.289,1,0.129,0.353,0.272,
    0.877,0.63,0.676,0.438,0.71,0.54,0.276,0.361,0.431,0.556,0.746,0.872,0.199,0.07,
    0.984,0.602,0.09,0.607,0.567,0.724,0.052,0.319,0.09,0.392,0.243,0.213,0.398,0.406,
    0.786,0.415,0.276,0.549,0.593,0.005,0.74,0.845,0.39,0.462,0.948,0.414,1,0.594,
    0.289,0.919,1,0.329,0.891,0.194,0.714,0.138,0.161,0.12,0.36,0.148,0.111,0.107,
    0.273,0.771,0.661,0.157,0.73,0.458,0.004,0.38,0.348,0.288,0.423,0.104,0.358,0.781,
    0.999,0.398,0.198,0.855,0.833,0.322,0.508,0.751,0.519,0.31,0.667,0.282,0.342,0.643,
    0.452,0.547,0.035,0.196,0.765,0.136,0.431,0.206,1,0.251,0.221,1,0.037,1,
    0.162,0.351,0.694,0.197,0.995,0.716,0.252,1,0.031,1,0.16,0.093,0.457,0.3,
    1,0.617,0.427,0.106,0.976,0.57,0.296,0.982,0.751,0.901,0.126,0.581,0.707,0.169,
    0.296,0.484,0.212,0.014,0.557,0.254,0.818,0.625,0.251,0.104,0.947,0.456,0.129,0.392,
    0.777,0.613,0.392,0.93,0.882,0.231,0.003,0.243,0.174,0.65,0.114,0.787,0.489,0.214,
    0.301,0.33,0.039,1,1,0.371,0.018,0.21,0.175,0.311,0.056,0.583,0.688,0.484;
enddata
end
```

# Appendix B

## Lingo code for the sub model I in chapter 5

```
model:

sets:
supplier/1..6/:W,B;
criterion/1..14/:Wm,PV;
s_value(supplier,criterion):V;
endsets

!************************************************************************************;
!W: the weights that can make the supply portfolio achieves the highest possible strategic value;
!VT: the total strategic value that supplier i has when the weight are w
!Wm: preferred weight in the weight ranges;
!V: the currant strategic value of supplier i regarding criterion j;
!B: binary variable assigned to each potential supplier;
!************************************************************************************;

@FOR(Criterion(j):PV(j)=@SUM(supplier(i):V(i,j)*W(i)));
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
!************************************************************************************;
max = @SUM(Criterion(j):Wm(j)*PV(j));

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
Wm=0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
V= 0.499,0.922,0.148,0.015,0.626,0.225,1,0.407,0.76,0.067,0.8,0.263,0.36,0.298,
    0.877,0.63,0.676,0.438,0.71,0.54,0.276,0.361,0.431,0.556,0.746,0.872,0.199,0.07,
    0.786,0.415,0.276,0.549,0.593,0.005,0.74,0.845,0.39,0.462,0.948,0.414,1,0.594,
    0.999,0.398,0.198,0.855,0.833,0.322,0.508,0.751,0.519,0.31,0.667,0.282,0.342,0.643,
    0.452,0.547,0.035,0.196,0.765,0.136,0.431,0.206,1,0.251,0.221,1,0.037,1,
    1,0.617,0.427,0.106,0.976,0.57,0.296,0.982,0.751,0.901,0.126,0.581,0.707,0.169;
enddata
end
```

# Appendix C

## Lingo code for the sub model II in chapter 5

```
model:

sets:
supplier/1..6/:W,B;
vartype/1..8/: ;
varvalue(supplier,vartype):RVAR;
endsets

!************************************************************************************;
!W: the weights can minimize portfolio's VaR value;
!B: binary varible assigned to each potential supplier;
!************************************************************************************;

VaR=@SUM(varvalue(i,j): RVAR(i,j)*W(i));
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
!************************************************************************************;
min = VaR;

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
RVAR=
170088, 312361, 856277, 456607, 994049, 677506, 715589, 711658,
431866, 262672, 382681, 913594, 85338, 773350, 525002, 982026,
479128, 41594, 806438, 652810, 317794, 523222, 632578, 477717,
720291, 505476, 57087, 774618, 265372, 173655, 482478, 296643,
761967, 729005, 364999, 341736, 167593, 349698, 915065, 729063,
793268, 475574, 168048, 64823, 726894, 156717, 745854, 447705;
enddata
end
```

# Appendix D

## Lingo code for the sub model III in chapter 5

```
model:

sets:
supplier/1..6/:W,B,MRATIO;
criterion/1..14/:Wm;
value(supplier,criterion):MTTDATA;
endsets

!********************************************************************************;
!W: the weights can minimize portfolio's beta value;
!Wm: preferred value of the criteria' weight ranges;
!MTTDATA: maximum MtT type risk value from a supplier regarding a criterion;
!MRATIO: the discount rate considering correlation;
!B: binary varible assigned to each potential supplier;
!********************************************************************************;

MTT=@SUM(value(i,j):MTTDATA(i,j)*MRATIO(i)*W(i));
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
!********************************************************************************;
min = MTT;

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
!Wm= 0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
MTTDATA=
76464, 40703, 61997, 120973, 31509, 88737, 30408, 90403,    90840, 109676, 72949, 41532,
61666, 95891,
129005, 81192, 107928, 76173, 124227, 84890, 126871, 53579, 35571, 73556, 85291,    65755,
78132, 83143,
60080, 76224, 118320, 90202, 120921, 79655, 49115, 129431, 96015, 32911, 112319,    40898,
64189, 99550,
56366, 116960, 87833, 47017, 98075, 44541, 56334, 124177, 69847,       79154, 99579, 96752,
116231, 109450,
116165, 77830, 109935, 121981, 39006, 55381, 51579, 33552, 51615, 113314, 111371, 50163,
44294, 121337,
97884, 106148, 87644, 105769, 82332, 91996, 126848,    55879, 74479, 87085, 72217, 83546,
90886, 128787;
MRATIO=0.85, 0.71, 0.77, 0.69, 0.74, 0.87;
enddata
end
```

# Appendix E

## Lingo code for the fuzzy goal programming model in chapter 5

```
model:

sets:
supplier/1..6/:W,B,MRATIO;
criterion/1..14/:Wm,PV;
vartype/1..8/:;
varvalue(supplier,vartype):RVAR;
value(supplier,criterion):MTTDATA,V;
endsets

!********************************************************************************;
!W: the weights can bring the best compromised solution;
!Wm: preferred value of the criteria' weight ranges;
!MTTDATA: maximum MtT type risk value from a supplier regarding a criterion;
!MRATIO: the discount rate considering correlation;
!B: binary variable assigned to each potential supplier;
!VT: the total strategic value that supplier i has when the weight are w;
!V: the currant strategic value of supplier i regarding criterion j;
!********************************************************************************;
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
@FOR(Criterion(j):PV(j)=@SUM(supplier(i):V(i,j)*W(i)));
STR=@SUM(Criterion(j):Wm(j)*PV(j));
VaR=@SUM(varvalue(i,j): RVAR(i,j)*W(i));
MTT=@SUM(value(i,j):MTTDATA(i,j)*MRATIO(i)*W(i));
M>=(0.658-STR)*1000;
M>=(VaR-3336273)/10000;
M>=(MTT-815653)/1000;
!********************************************************************************;
min = M;

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
!Wm= 0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
MTTDATA=
76464, 40703, 61997, 120973, 31509, 88737, 30408, 90403,   90840,   109676,   72949,   41532,
61666, 95891, 129005, 81192, 107928, 76173, 124227, 84890, 126871, 53579, 35571, 73556,
85291,     65755, 78132, 83143, 60080, 76224, 118320, 90202, 120921, 79655, 49115, 129431,
96015, 32911,  112319,   40898, 64189, 99550, 56366, 116960, 87833, 47017, 98075, 44541,
56334, 124177, 69847,    79154, 99579, 96752, 116231, 109450, 116165, 77830, 109935, 121981,
39006, 55381, 51579, 33552, 51615, 113314, 111371, 50163, 44294, 121337, 97884, 106148,
87644, 105769, 82332, 91996, 126848,   55879, 74479, 87085, 72217, 83546, 90886, 128787;
MRATIO=0.85, 0.71, 0.77, 0.69, 0.74, 0.87;
RVAR=
170088, 312361, 856277, 456607, 994049, 677506, 715589, 711658,
431866, 262672, 382681, 913594, 85338,   773350, 525002, 982026,
479128, 41594,   806438, 652810, 317794, 523222, 632578, 477717,
720291, 505476, 57087,   774618, 265372, 173655, 482478, 296643,
761967, 729005, 364999, 341736, 167593, 349698, 915065, 729063,
793268, 475574, 168048, 64823,   726894, 156717, 745854, 447705;
Wm=0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
V= 0.499, 0.922, 0.148, 0.015, 0.626, 0.225, 1, 0.407, 0.76, 0.067, 0.8,0.263, 0.36, 0.298, 0.877,
0.63, 0.676, 0.438, 0.71, 0.54, 0.276, 0.361, 0.431, 0.556, 0.746,0.872,0.199,0.07, 0.786, 0.415,
0.276, 0.549, 0.593, 0.005, 0.74, 0.845, 0.39, 0.462, 0.948, 0.414, 1, 0.594,      0.999, 0.398,0.198,
0.855, 0.833, 0.322, 0.508, 0.751, 0.519, 0.31, 0.667, 0.282, 0.342, 0.643, 0.452, 0.547,0.035,
0.196,0.765,0.136, 0.431,0.206, 1,0.251,0.221, 1, 0.037, 1, 1, 0.617, 0.427, 0.106, 0.976, 0.57,
0.296, 0.982, 0.751, 0.901, 0.126, 0.581, 0.707, 0.169;
enddata
end
```

# Appendix F

## Lingo code for the Non-preemptive goal programming model in chapter 5

```
model:

sets:
supplier/1..6/:W,B,MRATIO;
criterion/1..14/:Wm,PV;
vartype/1..8/:;
varvalue(supplier,vartype):RVAR;
value(supplier,criterion):MTTDATA,V;
endsets

!***********************************************************************************;
!W: the weights can bring the best compromised solution;
!Wm: preferred value of the criteria' weight ranges;
!MTTDATA: maximum MtT type risk value from a supplier regarding a criterion;
!MRATIO: the discount rate considering correlation;
!B: binary variable assigned to each potential supplier;
!VT: the total strategic value that supplier i has when the weight are w;
!V: the currant strategic value of supplier i regarding criterion j;
!***********************************************************************************;
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
@FOR(Criterion(j):PV(j)=@SUM(supplier(i):V(i,j)*W(i)));
STR=@SUM(Criterion(j):Wm(j)*PV(j));
VaR=@SUM(varvalue(i,j): RVAR(i,j)*W(i));
MTT=@SUM(value(i,j):MTTDATA(i,j)*MRATIO(i)*W(i));
VaR+N1-P1=3336273;
STR+N2-P2=0.658;
MTT+N3-P3=815653;
!***********************************************************************************;
min = 1000*(W1*P1/3336273+W2*N2/0.658+W3*P3/815653);

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
!Wm= 0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025, 0.016;
MTTDATA=
76464, 40703, 61997, 120973, 31509, 88737, 30408, 90403,   90840, 109676, 72949, 41532, 61666,
95891, 129005, 81192, 107928, 76173, 124227, 84890, 126871, 53579, 35571, 73556, 85291,65755,
78132, 83143, 60080, 76224, 118320, 90202, 120921, 79655, 49115, 129431, 96015, 32911,
      112319,   40898, 64189, 99550, 56366, 116960, 87833, 47017, 98075, 44541, 56334, 124177,
69847,    79154, 99579, 96752, 116231, 109450, 116165, 77830, 109935, 121981, 39006, 55381,
51579, 33552, 51615, 113314, 111371, 50163, 44294, 121337, 97884, 106148, 87644, 105769, 82332,
91996, 126848,   55879, 74479, 87085, 72217, 83546, 90886, 128787;
MRATIO=0.85, 0.71, 0.77, 0.69, 0.74, 0.87;
RVAR=
170088, 312361, 856277, 456607, 994049, 677506, 715589, 711658, 431866, 262672, 382681,
913594, 85338,  773350, 525002, 982026, 479128, 41594,  806438, 652810, 317794, 523222,
632578, 477717, 720291, 505476, 57087,  774618, 265372, 173655, 482478, 296643, 761967,
729005, 364999, 341736, 167593, 349698, 915065, 729063, 793268, 475574, 168048, 64823,
726894, 156717, 745854, 447705;
Wm=0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025, 0.016;
V= 0.499, 0.922, 0.148, 0.015, 0.626, 0.225, 1, 0.407, 0.76, 0.067, 0.8,0.263, 0.36, 0.298, 0.877, 0.63,
0.676, 0.438, 0.71, 0.54, 0.276, 0.361, 0.431, 0.556, 0.746,0.872,0.199,0.07, 0.786, 0.415, 0.276,
0.549, 0.593, 0.005, 0.74, 0.845, 0.39, 0.462, 0.948, 0.414, 1, 0.594,     0.999, 0.398,0.198, 0.855,
0.833, 0.322, 0.508, 0.751, 0.519, 0.31, 0.667, 0.282, 0.342, 0.643, 0.452, 0.547,0.035,
0.196,0.765,0.136, 0.431,0.206, 1,0.251,0.221, 1, 0.037, 1, 1, 0.617, 0.427, 0.106, 0.976, 0.57, 0.296,
0.982, 0.751, 0.901, 0.126, 0.581, 0.707, 0.169;
W1=0.2;
W2=0.5;
W3=0.3;
enddata
end
```

# Appendix G

## Lingo code 1 for the preemptive goal programming model in chapter 5

```
model:

sets:
supplier/1..6/:W,B,MRATIO;
criterion/1..14/:Wm,PV;
vartype/1..8/:;
varvalue(supplier,vartype):RVAR;
value(supplier,criterion):MTTDATA,V;
endsets

!************************************************************************************************************************;
!W: the weights can bring the best compromised solution;
!Wm: preferred value of the criteria' weight ranges;
!MTTDATA: maximum MtT type risk value from a supplier regarding a criterion;
!MRATIO: the discount rate considering correlation;
!B: binary variable assigned to each potential supplier;
!VT: the total strategic value that supplier i has when the weight are w;
!V: the currant strategic value of supplier i regarding criterion j;
!************************************************************************************************************************;
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
@FOR(Criterion(j):PV(j)=@SUM(supplier(i):V(i,j)*W(i)));
STR=@SUM(Criterion(j):Wm(j)*PV(j));
VaR=@SUM(varvalue(i,j): RVAR(i,j)*W(i));
MTT=@SUM(value(i,j):MTTDATA(i,j)*MRATIO(i)*W(i));
VaR<=3400000;
STR+N2-P2=0.658;
!************************************************************************************************************************;
min = N2;

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
!Wm= 0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
MTTDATA=
76464, 40703, 61997, 120973, 31509, 88737, 30408, 90403,   90840,   109676,   72949,   41532,
61666, 95891, 129005, 81192, 107928, 76173, 124227, 84890, 126871, 53579, 35571, 73556,
85291,    65755, 78132, 83143, 60080, 76224, 118320, 90202, 120921, 79655, 49115, 129431,
96015, 32911,  112319,   40898, 64189, 99550, 56366, 116960, 87833, 47017, 98075, 44541,
56334, 124177, 69847,    79154, 99579, 96752, 116231, 109450, 116165, 77830, 109935, 121981,
39006, 55381, 51579, 33552, 51615, 113314, 111371, 50163, 44294, 121337, 97884, 106148,
87644, 105769, 82332, 91996, 126848,   55879, 74479, 87085, 72217, 83546, 90886, 128787;
MRATIO=0.85, 0.71, 0.77, 0.69, 0.74, 0.87;
RVAR=
170088, 312361, 856277, 456607, 994049, 677506, 715589, 711658,
431866, 262672, 382681, 913594, 85338,   773350, 525002, 982026,
479128, 41594,   806438, 652810, 317794, 523222, 632578, 477717,
720291, 505476, 57087,   774618, 265372, 173655, 482478, 296643,
761967, 729005, 364999, 341736, 167593, 349698, 915065, 729063,
793268, 475574, 168048, 64823,   726894, 156717, 745854, 447705;
Wm=0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
V= 0.499, 0.922, 0.148, 0.015, 0.626, 0.225, 1, 0.407, 0.76, 0.067, 0.8,0.263, 0.36, 0.298, 0.877,
0.63, 0.676, 0.438, 0.71, 0.54, 0.276, 0.361, 0.431, 0.556, 0.746,0.872,0.199,0.07, 0.786, 0.415,
0.276, 0.549, 0.593, 0.005, 0.74, 0.845, 0.39, 0.462, 0.948, 0.414, 1, 0.594,      0.999, 0.398,0.198,
0.855, 0.833, 0.322, 0.508, 0.751, 0.519, 0.31, 0.667, 0.282, 0.342, 0.643, 0.452, 0.547,0.035,
0.196,0.765,0.136, 0.431,0.206, 1,0.251,0.221, 1, 0.037, 1, 1, 0.617, 0.427, 0.106, 0.976, 0.57,
0.296, 0.982, 0.751, 0.901, 0.126, 0.581, 0.707, 0.169;
W1=0.2;
W2=0.5;
W3=0.3;
enddata
end
```

# Appendix H

## Lingo code 2 for the preemptive goal programming model in chapter 5

```
model:

sets:
supplier/1..6/:W,B,MRATIO;
criterion/1..14/:Wm,PV;
vartype/1..8/:;
varvalue(supplier,vartype):RVAR;
value(supplier,criterion):MTTDATA,V;
endsets

!*********************************************************************************************;
!W: the weights can bring the best compromised solution;
!Wm: preferred value of the criteria' weight ranges;
!MTTDATA: maximum MtT type risk value from a supplier regarding a criterion;
!MRATIO: the discount rate considering correlation;
!B: binary variable assigned to each potential supplier;
!VT: the total strategic value that supplier i has when the weight are w;
!V: the currant strategic value of supplier i regarding criterion j;
!*********************************************************************************************;
@FOR(supplier(i):W(i)>=Wmin*B(i));
@FOR(supplier(i):W(i)<=Wmax*B(i));
@SUM(supplier(i):W(i))=1;
N=@SUM(supplier(i):B(i));
N>=Nmin;
N<=Nmax;
@FOR(supplier(i):@BIN(B(i)));
@FOR(Criterion(j):PV(j)=@SUM(supplier(i):V(i,j)*W(i)));
STR=@SUM(Criterion(j):Wm(j)*PV(j));
VaR=@SUM(varvalue(i,j): RVAR(i,j)*W(i));
MTT=@SUM(value(i,j):MTTDATA(i,j)*MRATIO(i)*W(i));
VaR<=3400000;
STR>=0.615;
!*********************************************************************************************;
min = MTT;

data:
Nmin=2;
Nmax=3;
Wmin=0.1;
Wmax=0.8;
!Wm= 0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
MTTDATA=
76464, 40703, 61997, 120973, 31509, 88737, 30408, 90403,   90840,   109676,   72949,   41532,
61666, 95891, 129005, 81192, 107928, 76173, 124227, 84890, 126871, 53579, 35571, 73556,
85291,    65755, 78132, 83143, 60080, 76224, 118320, 90202, 120921, 79655, 49115, 129431,
96015, 32911,  112319,   40898, 64189, 99550, 56366, 116960, 87833, 47017, 98075, 44541,
56334, 124177, 69847,    79154, 99579, 96752, 116231, 109450, 116165, 77830, 109935, 121981,
39006, 55381, 51579, 33552, 51615, 113314, 111371, 50163, 44294, 121337, 97884, 106148,
87644, 105769, 82332, 91996, 126848,   55879, 74479, 87085, 72217, 83546, 90886, 128787;
MRATIO=0.85, 0.71, 0.77, 0.69, 0.74, 0.87;
RVAR=
170088, 312361, 856277, 456607, 994049, 677506, 715589, 711658,
431866, 262672, 382681, 913594, 85338,   773350, 525002, 982026,
479128, 41594,   806438, 652810, 317794, 523222, 632578, 477717,
720291, 505476, 57087,   774618, 265372, 173655, 482478, 296643,
761967, 729005, 364999, 341736, 167593, 349698, 915065, 729063,
793268, 475574, 168048, 64823,   726894, 156717, 745854, 447705;
Wm=0.162, 0.030, 0.046, 0.032, 0.005, 0.017, 0.165, 0.071, 0.288, 0.096, 0.024, 0.024, 0.025,
0.016;
V= 0.499, 0.922, 0.148, 0.015, 0.626, 0.225, 1, 0.407, 0.76, 0.067, 0.8,0.263, 0.36, 0.298, 0.877,
0.63, 0.676, 0.438, 0.71, 0.54, 0.276, 0.361, 0.431, 0.556, 0.746,0.872,0.199,0.07, 0.786, 0.415,
0.276, 0.549, 0.593, 0.005, 0.74, 0.845, 0.39, 0.462, 0.948, 0.414, 1, 0.594,      0.999, 0.398,0.198,
0.855, 0.833, 0.322, 0.508, 0.751, 0.519, 0.31, 0.667, 0.282, 0.342, 0.643, 0.452, 0.547,0.035,
0.196,0.765,0.136, 0.431,0.206, 1,0.251,0.221, 1, 0.037, 1, 1, 0.617, 0.427, 0.106, 0.976, 0.57,
0.296, 0.982, 0.751, 0.901, 0.126, 0.581, 0.707, 0.169;
W1=0.2;
W2=0.5;
W3=0.3;
enddata
end
```

# Appendix I

## Lingo code for the example in chapter 6

```
model:

sets:
arc/1..2/:LL111,LL121,LL211,LC211,LC221,USC211,USC221,FSC211,FSC221,FSC311;
!LL111(a)         transportation lead-time from A to C' through arc a;
!LL121(a)         transportation lead-time from B to C' through arc a;
!LL211(a)         transportation lead-time from C' to C through arc a;
!LC211(a)         capacity constraints of arc a from A to C';
!LC221(a)         capacity constraints of arc a from B to C';
!USC211(a)        unit size shipping cost from A to C' by using arc a;
!USC221(a)        unit size shipping cost from B to C' by using arc a;
!FSC211(a)        fixed cost if there is a shipment from A to C' by using arc a;
!FSC221(a)        fixed cost if there is a shipment from B to C' by using arc a;
!FSC311(a)        fixed cost if the production line a from C' to C is running;
product/1..2/:S1,S2,NI31,NI41,NI42,UIC31,UIC41,UIC42,LSD,OSD,LSE,OSE,RCA,RCB,ECR;
!LSD(k)           Unit lost sale cost in D for product k;
!OSD(k)           Unit overstock cost in D for product k;
!LSE(k)           Unit lost sale cost in E for product k;
!OSE(k)           Unit overstock cost in E for product k;
!S1(k)            unit size in SUC of RI and RII;
!S2(k)            unit size in SUC of PI and PII;
!NI31(k)          starting inventory of product K in node C;
!NI41(k)          starting inventory of product K in node D;
!NI42(k)          starting inventory of product K in node E;
!UIC31(k)         unit inventory cost per time period for product k at C;
!UIC41(k)         unit inventory cost per time period for product k at D;
!UIC42(k)         unit inventory cost per time period for product k at E;
!RCA(k)              regular order unit cost for raw material k from A;
!RCB(k)              regular order unit cost for raw material k from B;
!ECR(k)              emergency order unit cost for raw material k;
time/1..8/:LD411,LD412;
!LD411(t)         1 if there is a shipment from C to D at time t or 0 otherwise;
!LD412(t)         1 if there is a shipment from C to E at time t or 0 otherwise;
ArPr(arc,product):LC311,USC311;
!LC311(a,k)      capacity for product k on production line a from C' to C;
!USC311(a,k)    unit production cost for product k from C' to C by using production line a;
ArTi(arc,time):LD211,LD221,LD311;
!LD211(a,t)      1 if arc a from A to C' is used at time t or 0 otherwise;
!LD221(a,t)      1 if arc a from B to C' is used at time t or 0 otherwise;
!LD311(a,t)      1 if arc a from C' to C is used at time t or 0 otherwise;
PrTi(product,time):XI411,XI412,XO311,XO312,D1,D2,N31,N41,N42,UD1,VD1,UD2,VD2,UD3,VD3,
UE1,VE1,UE2,VE2, UE3,VE3,DD1,DD2,DD3,DE1,DE2,DE3;
!UD1(k,t),UD2(k,t),UD3(k,t)      lost sale quantity for product k at time t in D;
!VD1(k,t),VD2(k,t),VD3(k,t)      overstock quantity for product k at time t in D;
!UE1(k,t),UE2(k,t),UE3(k,t)      lost sale quantity for product k at time t in E;
!VE1(k,t),VE2(k,t),VE3(k,t)      overstock quantity for product k at time t in E;
!XI411(k,t)      # of product k arrived in D from C at time t;
!XI412(k,t)      # of product k arrived in E from C at time t;
!XO311(k,t)      # of product k shipped out from C to D at time t;
!XO312(k,t)      # of product k shipped out from C to E at time t;
!D1(k,t)           demand quantities that the supply chain plans to satisfy in D at time t;
!D2(k,t)           demand quantities that the supply chain plans to satisfy in E at time t;
!N31(k,t)          # of product K at node C at time t;
!N41(k,t)          # of product K at node D at time t;
!N42(k,t)          # of product K at node E at time t;
ArPrTi(arc,product,time):XI211,XI221,XI311,XO111,XO121,XO211;
!XI211(a,k,t) # of M/C/P k arrived in C' from A through arc a at time t;
!XI221(a,k,t) # of M/C/P k arrived in C' from B through arc a at time t;
!XI311(a,k,t) # of product k arrived in C from C' through arc a at time t;
!XO111(a,k,t) # of product k shipped out from A to C' through arc a at time t;
!XO121(a,k,t) # of product k shipped out from B to C' through arc a at time t;
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!XO211(a,k,t) # of product k shipped out from C' to C through arc a at time t;
!***********OTHERS***************;
!LC411              capacity constraints of arc from C to D;
!LC412              capacity constraints of arc from C to E;
!C31                inventory capacity in C;
!C41                inventory capacity in D;
!C42                inventory capacity in E;
!USC411             unit size shipping cost from C to D;
!USC412             unit size shipping cost from C to E;
!FSC411             fixed cost if there is a shipment from C to D;
!FSC412             fixed cost if there is a shipment from C to E;
!LL311              transportation lead-time from C to D;
!LL312              transportation lead-time from C to E;
endsets

!************************* CONSTRAINTS**********************************;
!Initial flow-in variables in network;
XI211(1,1,1)=0;
XI211(1,2,1)=0;
XI211(2,1,1)=0;
XI211(2,2,1)=0;
XI221(1,1,1)=0;
XI221(1,2,1)=0;
XI221(2,1,1)=0;
XI221(2,2,1)=0;
XI221(2,1,2)=0;
XI221(2,2,2)=0;
XI311(1,1,1)=0;
XI311(2,2,1)=0;
XI411(1,1)=0;
XI411(2,1)=0;
XI412(1,1)=0;
XI412(2,1)=0;
WEEKS=8;
!Node related constraints: flow-in equals to flow-out in nodes;
!****layer 1****;
!****layer 2****;
@for(PrTi(k,t):@sum(arc(a):XI211(a,k,t)+XI221(a,k,t))=@sum(arc(a):XO211(a,k,t)));
!****layer 3****;
@for(product(k): NI31(k)=XO311(k,1)+XO312(k,1)+N31(k,1));
@for(PrTi(k, t)|t#GE#2:@sum(arc(a):XI311(a,k,t))+N31(k,t-1)=XO311(k,t)+XO312(k,t)+N31(k,t));
!****layer 4****;
@for(product(k): NI41(k)-D1(k,1)=N41(k,1));
@for(product(k): NI42(k)-D2(k,1)=N42(k,1));
@for(PrTi(k, t)|t#GE#2:XI411(k,t)+N41(k,t-1)-D1(k,t)=N41(k,t));
@for(PrTi(k, t)|t#GE#2:XI412(k,t)+N42(k,t-1)-D2(k,t)=N42(k,t));
!Node related constraints: Capacity constraints;
!****layer 1****;
!****layer 2****;
!****layer 3****;
@for(time(t):@sum(product(k):N31(k,t)*S2(k))<=C31);
!****layer 4****;
@for(time(t):@sum(product(k):N41(k,t)*S2(k))<=C41);
@for(time(t):@sum(product(k):N42(k,t)*S2(k))<=C42);
!Arc related constraints: flow-in equals to flow-out for arcs;
!****from layer 1 to layer 2****;
@for(ArPrTi(a,k,t)|t#LE#(WEEKS-LL111(a)):XO111(a,k,t)= XI211(a,k,t+LL111(a)));
@for(ArPrTi(a,k,t)|t#LE#(WEEKS-LL121(a)):XO121(a,k,t)= XI221(a,k,t+LL121(a)));
!****from layer 2 to layer 3 (production)****;
@for(time(t)|t#LE#(WEEKS-LL211(1)):XO211(1,1,t)/3=XI311(1,1,t+LL211(1)));
@for(time(t)|t#LE#(WEEKS-LL211(1)):XO211(1,2,t)/4=XI311(1,1,t+LL211(1)));
@for(time(t)|t#LE#(WEEKS-LL211(2)):XO211(2,1,t)/4=XI311(2,2,t+LL211(2)));
@for(time(t)|t#LE#(WEEKS-LL211(2)):XO211(2,2,t)/3=XI311(2,2,t+LL211(2)));
!production line 1 does not produce PII;
@for(time(t):XI311(1,2,t)=0);
!production line 2 does not produce PI;
@for(time(t):XI311(2,1,t)=0);
```

```
!****from layer 3 to layer 4****;
@for(PrTi(k, t)|t#LE#(WEEKS-LL311):XO311(k,t)= XI411(k,t+LL311));
@for(PrTi(k, t)|t#LE#(WEEKS-LL312):XO312(k,t)= XI412(k,t+LL312));
!Arc related constraints: Capacity constraints;
!****from layer 1 to layer 2****;
@for(ArTi(a,t):@sum(product(k):XI211(a,k,t)*S1(k))<=LC211(a)*LD211(a,t));
@for(ArTi(a,t):@sum(product(k):XI221(a,k,t)*S1(k))<=LC221(a)*LD221(a,t));
!****from layer 2 to layer 3 (production)****;
@for(time(t): XI311(1,1,t)<= LC311(1,1)*LD311(1,t));
@for(time(t): XI311(2,2,t)<= LC311(2,2)*LD311(2,t));
!****from layer 3 to layer 4****;
@for(time(t):@sum(product(k):XI411(k,t)*S2(k))<=LC411*LD411(t));
@for(time(t):@sum(product(k):XI412(k,t)*S2(k))<=LC412*LD412(t));
!****************************** C O S T *******************************************;
!CA          transportation cost;
!CA211       transportation cost from A to C';
!CA221       transportation cost from B to C';
!CA311       production cost from C' to C;
!CA411       transportation cost from C to D;
!CA421       transportation cost from C to E;
!CLS41       lost sale cost and overstock cost at D;
!CLS42       lost sale cost and overstock cost at E;
!CN          Inventory cost in nodes;
!CN31        Inventory cost in C;
!CN41        Inventory cost in D;
!CN42        Inventory cost in E;
!CROA        Total expected order cost from A;
!CROB        Total expected order cost from B;

CA211=@sum(ArTi(a,t):@sum(product(k):XI211(a,k,t)*S1(k))*USC211(a)+FSC211(a)*LD211(a,t));
CA221=@sum(ArTi(a,t):@sum(product(k):XI221(a,k,t)*S1(k))*USC221(a)+FSC221(a)*LD221(a,t));
CA34=@sum(ArPrTi(a,k,t):XI311(a,k,t)*USC311(a,k) + FSC311(a)*LD311(a,t));
CA411=@sum(time(t):@sum(product(k):XI411(k,t)*S2(k))*USC411+LD411(t)*FSC411);
CA421=@sum(time(t):@sum(product(k):XI412(k,t)*S2(k))*USC412+LD412(t)*FSC412);
CA=CA211+CA221+CA34+CA411+CA421;
@for(PrTi(k,t):UD1(k,t)-VD1(k,t)=DD1(k,t)-D1(k,t));
@for(PrTi(k,t):UD2(k,t)-VD2(k,t)=DD2(k,t)-D1(k,t));
@for(PrTi(k,t):UD3(k,t)-VD3(k,t)=DD3(k,t)-D1(k,t));
@for(PrTi(k,t):UE1(k,t)-VE1(k,t)=DE1(k,t)-D2(k,t));
@for(PrTi(k,t):UE2(k,t)-VE2(k,t)=DE2(k,t)-D2(k,t));
@for(PrTi(k,t):UE3(k,t)-VE3(k,t)=DE3(k,t)-D2(k,t));
CLS411=@sum(PrTi(k,t):(UD1(k,t)*LSD(k)+VD1(k,t)*OSD(k))*PD1);
CLS412=@sum(PrTi(k,t):(UD2(k,t)*LSD(k)+VD2(k,t)*OSD(k))*PD2);
CLS413=@sum(PrTi(k,t):(UD3(k,t)*LSD(k)+VD3(k,t)*OSD(k))*PD3);
CLS41=CLS411+ CLS412+ CLS413;
CLS421=@sum(PrTi(k,t):(UE1(k,t)*LSE(k)+VE1(k,t)*OSE(k))*PE1);
CLS422=@sum(PrTi(k,t):(UE2(k,t)*LSE(k)+VE2(k,t)*OSE(k))*PE2);
CLS423=@sum(PrTi(k,t):(UE3(k,t)*LSE(k)+VE3(k,t)*OSE(k))*PE3);
CLS42=CLS421+CLS422+CLS423;
CN31 = @sum(PrTi(k,t):N31(k,t)*UIC31(k));
CN41 = @sum(PrTi(k,t):N41(k,t)*UIC41(k));
CN42 = @sum(PrTi(k,t):N42(k,t)*UIC42(k));
CN = CN31+CN41+CN42;
CROA = @sum(ArPrTi(a,k,t):XO111(a,k,t)*RCA(k));
CROB = @sum(ArPrTi(a,k,t):XO121(a,k,t)* RCB(k));
!Binary variables;
@FOR(ArTi:@BIN(LD211));
@FOR(ArTi:@BIN(LD221));
@FOR(ArTi:@BIN(LD311));
@FOR(time:@BIN(LD411));
@FOR(time:@BIN(LD412));
CTOTAL=CA+CN+CLS41+CLS42+CROA+CROB;
CTOTAL<=177842;
MA = @sum(ArPrTi(a,k,t):XO111(a,k,t)*(0.02*0.01*20+0.02*0.02*20+0.01*0.05*20 ));
MB = @sum(ArPrTi(a,k,t):XO121(a,k,t)*(0.04*0.01*20+0.03*0.02*20+0.03*0.05*20 ));
MA+MB<=761;
!MA: Total MtT type risks from A;
!MB: Total MtT type risks from B;
```

```
AVAR1=3.13*CROA+7234.12;
AVAR2=5.3*CROA;
AVAR3=4.7*CROA+121;
BVAR1=2.92*CROB+8235.72;
BVAR2=3.7*CROB+3451.23;
BVAR3=4.6*CROB;
MVAR =AVAR1+AVAR2+AVAR3+BVAR1+BVAR2+BVAR3;
!************************* minimize total cost ************************************;
Min = MVAR;
!************************************************************************************;
data:
LL111 = 1, 1;
LL121 = 1, 2;
LL211 = 1, 1;
LL311 = 1;
LL312 = 1;
LC211 = 2500, 4000;
LC221 = 2500, 5000;
LC311 = 650, 0, 0, 600;
LC411 = 5800;
LC412 = 4500;
C31 = 4000;
C41 = 4500;
C42 = 5000;
S1 = 1, 2;
S2 = 3, 3;
NI31 = 520,500;
NI41 = 550,400;
NI42 = 550,400;
DD1 = 210, 190, 230, 330, 150, 270, 210, 190, 130, 230, 170, 200, 260, 230, 130, 210;
DE1 = 120, 240, 180, 190, 250, 230, 120, 190, 220, 180, 240, 320, 160, 260, 220, 270;
DD2 = 200, 180, 220, 320, 140, 260, 200, 180, 120, 220, 160, 190, 250, 220, 120, 200;
DE2 = 110, 230, 170, 180, 240, 220, 110, 180, 210, 170, 230, 310, 150, 250, 210, 260;
DD3 = 185, 165, 205, 305, 125, 245, 185, 165, 105, 205, 145, 175, 235, 205, 105, 185;
DE3 = 95, 215, 155, 165, 225, 205, 95, 165, 195, 155, 215, 295, 135, 235, 195, 245;
FSC211 = 500, 1000;
FSC221 = 1500, 2500;
FSC311 = 600, 500;
FSC411 = 1000;
FSC412 = 800;
USC211 = 3, 2;
USC221 = 2, 1;
USC311 = 3, 10, 10, 3;
USC411 = 2;
USC412 = 2;
UIC31 = 2, 2;
UIC41 = 4, 3;
UIC42 = 3, 4;
LSD = 80, 78;
OSD = 7, 7;
LSE = 78,86;
OSE = 6, 8;
PD1 = 0.15;
PE1 = 0.15;
PD2 = 0.75;
PE2 = 0.75;
PD3 = 0.1;
PE3 = 0.1;
RCA = 1.2, 1.5;
RCB = 1.0, 1.3;
enddata
end
```

# Curriculum Vitae

The Author was born in China, on July 12, 1974. He attended Huazhong University of Science and Technology from 1992 to 2000, and received a B.S. degree in 1996 and a M.S. degree in 2000. He came to the Pennsylvania State University in the Fall of 2001 and began graduate studies in Industrial Engineering and Operations Research. He received the Engineering Dean’s Fellowship in 2002, 2003, and 2004, and the Graduate Fellowship in 2002. He pursued his research in supply chain management and risk management under the direction of Professor A. Ravi Ravindran and received a dual title M.S. degree in 2004.