AN INTEGRATED FUZZY MULTI-CRITERIA DECISION MAKING METHOD FOR SUPPLIER EVALUATION

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AN INTEGRATED FUZZY MULTI-CRITERIA DECISION MAKING METHOD FOR SUPPLIER EVALUATION

by

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LIST OF ABBREVIATIONS

DEMATEL	Decision Making Trial and Evaluation Laboratory
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CCDEA	Chance Constrained Data Envelopment Analysis
CCP	Chance Constrained Programming
CFCS	Converting Fuzzy Data into Crisp Scores
DEA	Data Envelopment Analysis
FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
FDEMATEL	Fuzzy Decision Making Trial and Evaluation Laboratory
FMADM	Fuzzy Multi- Attribute Decision Making
FMODM	Fuzzy Multi- Objective Decision Making
FMOP	Fuzzy Multi- Objective Programming
MADM	Multi- Attribute Decision Making
MCDM	Multi- Criteria Decision Making
MOP	Multi- Objective Programming

MODEL GABUNGAN PEMBUATAN KEPUTUSAN ATRIBUT BERGANDA KABUR BAGI PENILAIAN PEMBEKAL

ABSTRAK

Penyelidikan ini bertujuan untuk mengkaji risiko yang timbul daripada kos, kualiti, penghantaran dan fleksibiliti bagi penilaian pembekal. Model gabungan kaedah yang terdiri daripada DEMATEL dan ANP yang berasaskan teori set kabur iaitu teori yang digunakan untuk menilai subjektiviti (kabur) dalam pembuatan keputusan, bertujuan untuk menangani masalah interaksi dan maklum balas antara kriteria apabila menjana pemberat yang berbeza untuk objektif bagi masalah hubungan rangkaian. Pemberat yang didapati melalui proses rangkaian perbandingan dari segi pasangan FANP akan digunakan dalam pengatucaraan objektif berganda kabur (FMOP) bersama dengan kapasiti dan permintaan kekangan untuk menentukan kuantiti pesanan optimum yang perlu diperuntukkan kepada pembekal. Kemudian, kaedah visual akan digunakan untuk membantu pembuat keputusan mengenalpasti hubungan interaksi antara kriteria. Analisis sensitiviti juga dijalankan untuk menilai tahap kepuasan objektif yang lain dengan mengawal tahap kepuasan kos pembelian. Gabungan kaedah ini dibuktikan dengan menjalankan kajian kes.

Dalam analisis fasa pertama, hasil kajian mendedahkan bahawa kualiti dan fleksibiliti merupakan penyebab kriteria, manakala kos dan penghantaran adalah kesan kriteria. Dalam analisi fasa kedua, hasil kajian menunjukkan bahawa kualiti adalah kriteria yang paling penting bagi syarikat, diikuti dengan kos pembelian, penghantaran dan fleksibiliti, dimana keputusan dalam analysis ini adalah searah dengan dengan analisis fasa pertama. Walau bagaimanapun, apabila hubungan interaksi dan maklum balas di antara kriteria diabaikan, kos pembelian berada di kedudukan pertama, diikuti dengan kualiti, penghantaran dan fleksibiliti, iaitu menunjukkan susunan kepentingan kriteria yang berbeza. Secara keseluruhan, dari segi peratusan, keputusan FMOP menunjukkan terdapat sedikit perbezaan dalam keseluruhan tahap kepuasan dan nilai objektif apabila pemberat objektif ditentukan oleh model cadangan iaitu DEMATEL kabur dan ANP kabur dan model tradisional AHP kabur.

Kata Kunci: Penilaian risiko pembekal; pengurusan rangkaian bekalan; pengatucaraan objektif berganda kabur.

AN INTEGRATED FUZZY MULTI-CRITERIA DECISION MAKING METHOD FOR SUPPLIER EVALUATION

ABSTRACT

This research investigates the risk exposure arising from the supplier evaluation criteria of cost, quality, delivery, and flexibility of the supplier. An integrated method of Decision Making Trial and Evaluation Laboratory (DEMATEL) and Analytic Network Process (ANP), drawn from fuzzy set theory to capture the subjectivity in the decision rating, is used to address the interaction and feedback effects between the criteria when generating the different weights of the objectives for a network relationship problem. These weights, which are found through FANP pairwise comparisons, are then incorporated into a fuzzy multi-objective programming (FMOP) problem with capacity and demand constraints to determine the optimal order quantity allocated to the suppliers. A visualization method is then used to help the decision maker identify the interdependencies of the criteria under evaluation. A sensitivity analysis is also conducted to examine the trade-off of the satisfaction level among the multiple objectives by controlling the degree of satisfaction of the cost. This integrated method is validated through a case study.

The first phase of analysis reveals that quality and flexibility are causal criteria, while cost and delivery are effect criteria. The second phase of analysis indicates that quality is the most important criterion for the company, followed by cost, delivery and flexibility, which tallies with the priority ranking in the first phase of the analysis. However, when the interaction and feedback relationships among the evaluation criteria are ignored, cost is ranked first, followed by quality, delivery and flexibility. Overall, the results yielded by solving FMOP indicate that there are slight differences in the overall satisfaction level and the values of objectives when the weight of objectives are determined by the proposed integrated fuzzy Decision Making Trial and Evaluation Laboratory (FDEMATEL) and fuzzy Analytic Network Process (FANP), and traditional method fuzzy Analytic Hierarchy Process (FAHP).

Keywords: Supplier risk assessment; Supply chain management; Fuzzy multi-objective programming.

CHAPTER 1
INTRODUCTION

1.1 Introduction

Evidence suggests that more than 60 percent of a firm's total purchases are related to purchases in raw materials and/ or component parts and services (Krajewski and Ritzman, 2002). These purchases are more significant (70 - 80 percent) for firms in the manufacturing and high-technology industries (Ghodsypour and O'Brien 1988; Weber et al., 1991). Reliance on third party suppliers and merchants exposes the firm to risks. Supplier related failures manifest as delivery failures, cost overruns, and quality compromises. Hence, reducing the risks in purchasing directly improves the profit margin and the overall competitiveness of the firm.

One way to mitigate the risk in the supply chain is to manage the supplier evaluation and selection process. Selecting the right suppliers lowers the risk of a supply chain disruption as wastage is reduced, quality failure minimized, and lead times and flexibility are improved (Kumar et al., 2004). Thus, there is a need to evaluate suppliers along the supply chain in terms of their risk exposures. By investigating the sources of supply chain risk, a comprehensive purchasing decision making tool that best fits the firm's requirements can be developed (Zsidisin, 2003a).

In practice, feedback and interrelationships between criteria are common (Tzeng et al., 2007). Risks can be influenced by these interrelationships through factors such as cost, quality, flexibility, economic environment and supplier confidence level (Kull and Talluri, 2008; Wu et al., 2010). For instance, feedback relationships occur between product quality and purchasing cost (i.e. high quality products lead to high purchasing cost), as well as supplier flexibility and supplier confidence level (i.e. higher levels of supplier flexibility increase the supplier's standing as a dominant player in the industry). For a decision maker to have an accurate supplier analysis in achieving maximum profit, this suggests the need to consider all the network effects, both independent and dependent relationships among the criteria in the evaluation process.

The following sections provide the research outline of the thesis. First, the research background of the study will be briefly explained. Throughout the brief description of the background of supplier selection based risk exposure using multi-criteria decision making (MCDM) method, the problem statement captures the research gap concerning the state-of-art of the existing research area such as the lack of consideration of the interrelationships among risk objectives in a supplier selection problem. Then, the research objectives are discussed. Finally, the significance of the study, definition of key terms and organization of the thesis are described.

1.2 Background of the Study

According to the review in Weber et al. (1991), the research on supplier has been ongoing since 1966. The proliferation of this research has attracted a review on the development in the field of supplier selection. The comprehensive review of supplier selection from 1966 to 2012 can be obtained from the following studies (i.e. Weber et al., 1991; Degraeve et al., 2000; De Boer et al., 2001; Ho et al., 2010; Chai et al., 2012).

It is no surprise that risk issues in supplier selection studies have been explored and constantly receiving the attention of both practitioners and academics. The focus of supply chain managers in supply chain risk becomes more apparent when industries have learnt some remarkable lessons from witnessing the impact of suppliers' failures that caused major disruptions in the supply chain. For instance, in the year 1997, supplier delivery failure has caused Boeing to bear the loss of an estimated $2.6 billion (Radjou, 2002). Another well known example is the small fire that occurred in sub-supplier's (Philips) plant causing Ericsson $400 million in year 2000 (Tang, 2006). In July 2007, an earthquake that caused severe damaged to the supplier (Riken Corporation) that supplied the products of piston and seal rings to the Toyota Motor Corporation caused production to halt in all Japanese factories (Blackhurst et al., 2008). Past histories of supplier failures have increased the awareness of industry in reducing the supply risks.

However, past experiences demonstrate that there is no simple recipe for evaluating and managing risks (Klinke and Renn, 2002), especially when risk evaluation involves the evaluation of multi-stakeholder, multi-criteria or at least partially conflicting criteria, in the sense that factors affecting the decisions are often intertwined. In addition, the subjectivity in the decision making process that often leads to the ambiguity due to the lack of risk information or the compromised quality of information added the challenges of decision makers on how to evaluate the risk problems effectively.

A means to overcome such problems is to introduce a method to determine the risk performance from information loss in order to preserve the quality of that decision. What managers need in making purchasing decisions is a formalized analytical framework that will aid them to select the best suppliers as well as to generate long term value of the company by avoiding supply chain disruptions. The field of MCDM readily provides this means of capturing the subjective and objective judgment of decision makers to weight, rank, select and optimize risk parameters in the supply chain when accurate and complete risk data are not available. Techniques such as the Decision Making Trial and Evaluation Laboratory (DEMATEL) as proposed by Gabus and Fontela (1972) and Analytic Network Process (ANP) by Saaty (1996) have been developed to handle problems with the inter-related factors based subjective and objective information.

In the past, a number of multi-attribute decision making (MADM) methodologies has been employed in capturing the risk exposures in the supplier selection context. However, most of the studies did not consider the interdependencies of the risk criteria (Wu et al., 2006; Levary, 2007), with a few dealing with the goal programming (Kull and Talluri, 2008), and multi-objective programming (MOP) (Wu et al., 2010; Wu et al., 2013; Yu and Goh, 2014), by assuming supplier risk objectives are independent of each other along with a set of constraints.

However, none of the studies conducted so far has investigated the interdependent relationships among the risk criteria and risk objectives in the supplier evaluation framework. Practically, if the factors are deemed interdependent, one has to consider the manner of integrating feedback as well as the interaction effects as a means to avoid decision makers to restrict their preferences, which ultimately affects the accuracy of the evaluation results.

In addition, the increase in outsourcing activities due to globalization has grown the complexity of the supply networks (Harland et al., 2003). These have directly contributed to the complexity of the relationships of the supply chain risk factors. Since an effective mitigation strategy is influenced by the degree of understanding of the variety and interconnected supply chain risks (Chopra and Sodhi, 2004), the interaction and interdependence relationships among the evaluation criteria are crucial and should be taken into account in the evaluation process. Thus, a supplier selection framework in choosing a set of suitable suppliers with optimal quantity allocation must be able to capture the complexity of the relationships (i.e. independent and interdependent).

1.3 Problem Statement

Interaction and interdependence among objectives (criteria) must be taken into account if the decision maker is to seek for a more accurate evaluation based on his/ her preference. However, majority of studies dealing with risk exposures in supplier selection assumed evaluation criteria to be independent of one another.

The aim of this thesis is to consider the interaction of suppliers' risk objectives (criteria) as well as to determine the optimal amount to be purchased from the selected suppliers by integrating fuzzy multi-attribute decision making (FMADM) and fuzzy multi-objective decision making (FMODM) approaches in supplier selection context. FMODM consists of the fuzzy treatment made to DEMATEL and ANP to better capture the subjectivity of a decision maker's response.

Furthermore, having considered the relationship effects in the evaluation framework, one has to address the extent that a final outcome in terms of quantity allocation decision is impacted by assuming that all the criteria are independent of each other when they are interdependent. Thus, it is important to investigate the interaction and feedback effects among risk measures in the supply chain. This thesis compares the proposed combination of MCDM, which is fuzzy DEMATEL (FDEMATEL) and fuzzy ANP (FANP) in determining the objective weights of fuzzy multi-objective programming (FMOP) with traditional method of fuzzy

Analytic Hierarchy Process (FAHP) in FMOP supplier evaluation. To illustrate the proposed method in a real-world application, a case study is also presented.

1.4 Objectives of the Study

The main objective of this thesis is to show the importance of incorporating both independent and interdependent relationships of objectives and its impact through the following initiatives:

i) To develop a supplier selection system by identifying and determining the cause and effect of risk criteria in supplier selection decision.

ii) To compare the objective weights obtained from the proposed hybrid of FDEMATEL and FANP against the traditional method which incorporates fuzzy set theory and Analytic Hierarchy Process (AHP).

iii) To examine the impact of objective weights derived by using the hybrid of FDEMATEL and FANP and traditional method FAHP on the final output of FMOP.

1.5 Significance of the Research

In terms of academic significance, this study attempts to analyze the implications of considering interaction and feedback effects among multiple objectives, which is aimed at discovering the different importance of weights placed on the objectives could affect the final decision. By capturing these effects strongly, it narrows the gap between the real-world problems and the mathematical formulation. This subsequently provides more accurate weights to generate the quota allocation for the suppliers.

In addition, an evaluation framework that combines FMADM and FMODM was developed. There has been some work that incorporate supply risks in the supplier assessment using DEMATEL (Hsu et al., 2013) and FANP (Yücenur et al., 2011), but not in a holistic manner. Furthermore, there is no work that explores combining fuzzy set theory with the hybrid method comprising of DEMATEL and ANP in FMOP supplier selection model based on supply risk exposure. This integrated method is useful and provides some coherence to the advantages of existing methodologies concerning this hybrid method.

1.6 Definition of Key Terms

This section describes the meaning of key terms employed in this thesis.

1. **Risk -** undesired outcomes which include potential cost increase, potential lost customer (Kull and Talluri, 2008) or uncertainty to the achievement of goals, objectives, criteria, or desire decision outcome (Frank, 1995).

2. **Supply risk -** originates from individual supplier failures which may lead to the issues with price, quantity and delivery, and may subsequently have an impact on the financial goal of the firm (Zsidisin, 2003b).

3. **Supply chain risk management -** tactics used to mitigate supply chain risk through the coordination or collaboration among supply chain partners to ensure profitability and continuity of the flows in the chain (Tang, 2006).

4. **Sand cone model concept -** based on the concept provided by Ferdows and De Meyer (1990), in sand cone model, resources and management attention should first improve the quality at the lowest level of

the cone to provide a stable foundation before other criteria (such as dependability, flexibility and cost) are enhanced at higher levels of the cone.

5. **Degree of influential impact -** the degree of all direct and indirect influence of one criterion over others (Zhou et al., 2011).

6. **Degree of influenced impact -** the degree of all direct and indirect influence received by one criterion from other criteria (Zhou et al., 2011).

1.7 Organization of the Thesis

Chapter 1 gives a brief overview of the supplier selection based risk exposures and descriptions on MCDM models.

Chapter 2 provides a brief introduction of MCDM in both certain and uncertain environments, including a review of supply chain risk management and supply based risk. A literature review of past work on MADM and multi-objective decision making (MODM) methodologies for supplier selection based risk factors is also presented.

In Chapter 3, the proposed three-stage research methodology is presented. First, FDEMATEL is applied to recognize and address the interrelationships between supplier risk criteria. Second, FANP is utilized to set relative weights of the evaluation criteria in FMOP. Third, FMOP is developed to generate the optimal set of suppliers and to determine the optimal amount of order quantities.

Following that, Chapter 4 presents detailed findings of the study. The main focus is on the evaluation and interpretation of the results and findings. Results of proposed method under study are discussed and compared with the traditional method of FAHP - FMOP.

In Chapter 5, research findings are summarized with conclusions about the importance of selecting the appropriate approach in calculating the priority weight of objectives in fuzzy linear programming. Lastly, the limitations of the study are described in tandem with the recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This section begins with a brief introduction to MCDM and FMCDM. Then, literature on supply chain risk management, which discusses the basic concepts of risk, supply risk and supply chain risk management is presented. Following that, the supply based risk which specifically focuses on the criteria of quality, cost, delivery and flexibility in determining the best supplier with optimal quantity allocation is discussed in detail. Finally, literature regarding the MADM and MODM methodologies on supplier selection based risk and uncertainty is presented.

2.2 Introduction to MCDM

MCDM is a flexible methodology that is used to deal with quantitative, qualitative or mixed data. Quantitative data refers to the statistical values, qualitative data refers to the linguistic rating given from human intuition, while mixed data is a combination of the two. MCDM is employed to aid the decision maker in solving complicated problems. In practical decision making situations, there may be a wide range of conflicting criteria and alternatives to be evaluated. Criteria can be defined as the aspects or dimensions of the problem context to be evaluated in achieving the goal, whereas the alternatives are referred to as a set of feasible choices (i.e. strategies) to be evaluated by the decision maker(s) so that the optimal decision would reveal the best alternative (i.e. strategy) based on the evaluation criteria. Determine the priority importance of the criteria as well as selecting of the best alternative within available alternatives is always difficult for the decision maker.

During the MCDM process, the data reflecting the importance/ preference placed on the criteria (whether quantitative, qualitative or mixed) are integrated, summarized into an overall aggregation scores. Although these scores/ weights in MCDM do not lead to clear economic significance, the MCDM models enable the actual aspects of decision making problems (preference structure) to be modeled according to the preference of decision makers (Opricovic and Tzeng, 2004). It becomes much easier and possible to evaluate unstructured decision problems (i.e. no standard solution approach or no precise data) that can ensure the reliability of the outcomes resulting from MCDM provided that the chosen decision maker has a good understanding of the problem at hand.

MCDM problems in general are segregated into two categories: MADM and MODM (Hwang and Yoon, 1981). MADM approaches are used to select the alternative or determine the order ranking of the evaluation alternatives by aggregating the information from the problem's decision matrices and decision maker (Tzeng and Huang, 2011). The evaluations of MADM are soft. That is, they allow purely subjective judgments from the decision maker to assist the modeling process especially in situations where accurate and complete data are lacking. These approaches are useful when it comes to solve and analyze many real-world problems where statistical data is hard to come by.

On the other hand, MODM approaches solve problems with multiple objective functions simultaneously subject to a set of constraints. Multiobjective optimization may not generate a unique solution, but it helps decision makers identify a set of efficient, nondominated or Pareto optimal solutions with respect to limited resources. Compared to MADM, MODM is likely to involve objective information. The evaluations of MODM are hard due to the fact that MODM not only has to generate the order ranking of alternatives, but also to determine the quantity allocation for the evaluation alternatives.

Decision making generally involves three main steps; 1) understand and define the problem, 2) collect the related information to analyze feasible alternatives, and 3) select and implement the best alternative to maximize the utility. The overall MCDM procedure, from problem identification to the best alternative selection is presented as follows (Lu et al., 2007):

- Identify the Decision Problem.
- Determine the Goals and Objectives.
- Determine the Alternatives.
- Establish the Evaluation Criteria if Necessary.
- Select an Appropriate MCDM Approach to Problem Structuring.
- Assess the Alternatives.
- Select the Best Alternative for the Problem Statements.

2.2.1 Identify the Decision Problem

The first step in making a decision is to recognize and understand the decision problem. To achieve this, the right expert analyst for the problem is required as the judgment made by the decision maker will be used as input for model evaluation. Identifying the decision problem is the most crucial and important step in preparing a clear problem statement. This research aims to select suitable suppliers based supplier risk factors by interviewing the manager of the company.

2.2.2 Determine the Goals and Objectives

After determining the problem statement, it is necessary to identify the goals and objectives of the decision. Goals provide a target level to achieve by limiting and restricting the alternative set and thus they can be referred as constraints. On the other hand, objectives are used for the indication of the direction to be pursued by the decision maker. In practice, different objectives will have different importance weights according to the preference of the decision maker. We consider four objectives in this study: cost, quality, delivery and flexibility.

2.2.3 Determine the Alternatives

With the objectives and goals of decision makers at hand, feasible alternatives for the problem evaluation are determined. In this study, three suppliers (supplier 1, supplier 2, supplier 3) are selected as the alternatives.

2.2.4 Establish the Evaluation Criteria if Necessary

The purpose of having evaluation criteria is to compare and to distinguish the alternatives based on the goals and objectives. For the model construction of this study, the evaluation criteria include supplier capacity, customer demand and the four objectives as mentioned above (refer Section 2.2.2).

2.2.5 Select an Appropriate MCDM Approach to Problem Structuring

Having a large number of alternatives with respect to a set of criteria in making decisions is becoming standard practice. Hence, it is difficult for the decision maker to manually make a wise and optimized decision. MCDM is an intelligent approach applied in synthesizing the rating of each criterion and alternative to determine the appropriate final preference ranking of alternatives. In this study, FDEMATEL and FANP are used to rank the interdependent criteria, while MODM is used to optimize multiple objectives in supplier selection.

2.2.6 Assess the Alternatives

Once the MCDM method is chosen, each alternative with respect to the determined criteria in Section 2.2.4 will be evaluated using quantitative and/ or qualitative information. Decision makers play an important role in assessing the criteria weights. Inappropriate assigned rating can lead to the inaccurate results and increase the risk of loss (e.g. cost increase). This research aims to determine the optimal amount of quantity to be purchased from the appropriate selected suppliers.

2.2.7 Select the Best Alternative for the Problem Statements

The alternative with the best fit to the decision maker's preferences will be chosen as the optimal decision. There are different methods in selecting the best alternative, depending on which approach is used. In the MCDM application, the most commonly used techniques are MADM and MODM. For the MADM approach, the alternative with the highest importance weight among the alternatives is selected. Meanwhile, for the MODM approach, the alternatives that best fit the model are determined based on the information data of each of the objectives and the resource constraints.

2.3 Introduction to Fuzzy MCDM

Fuzzy set theory was first introduced by Zadeh (1965) to handle the sources of imprecision such as vagueness of human thoughts due to incomplete, ambiguous, non-obtainable or unquantifiable information (Lin and Wu, 2008; Wu and Lee, 2007). Subsequently, this theory was applied by Bellman and Zadeh (1970) to describe decision making using mathematical techniques in fuzzy environment. After that, an increasing number of studies integrated fuzzy set theory with MADM (e.g. Yucenur et al., 2011; Lu et al., 2007) and MODM (e.g. Amid et al., 2006; Wu et al., 2010).

In the real world, there are many cases where it is not possible to obtain precisely defined data in numeric form. For example, in the supplier selection problem, it is difficult for decision makers to evaluate the performance of supplier flexibility and confidence level precisely and thus linguistic variable come in handy. A linguistic variable is a variable whose values are expressed in words or sentences instead of numbers. The concept of linguistic variables allows humans to deal with the difficulty of expressing opinions in overtly complex or hard to define problems (Zadeh, 1975). To tackle the imprecision and ambiguities that might exist in the process of linguistic estimation, fuzzy numbers are used to represent the linguistic judgment of the evaluator. In this study, a hybrid method by integrating fuzzy set theory with the DEMATEL, ANP and MOP is proposed in supplier selection.

2.4 Supply Chain Risk Management

The concept "risk" is impossible to be defined uniquely. Risk in practice is varied, which is depending on the different application contexts (Sonnemann et al., 2004; Lavasani et al., 2011). However, despite the different definitions, risk is generally referred to as undesirable outcomes including potential cost increase, potential lost customer (Kull and Talluri, 2008) or uncertainty to the achievement of goals, objectives, criteria, or desired decision outcome (Frank, 1995).

In the area of supply chain management, risk is viewed as the disruption caused on a supply chain's ability to continue operations, get finished goods to market, or provide critical services to customers (Juttner et al., 2003). For instance, the occurrence of supply chain disruptions that lead to the effects of long lead-times, stock-out and the failure to meet customer order which subsequently brings negative impact to a firm's financial performance (Blackhurst et al., 2008).

Supply chain risk can be classified as either operational or disruption risks (Tang, 2006), or internal risks and external risks (Goh et al., 2007). Operational risks are associated with the uncertainties in the coordination of supply and demand, while disruption risks refer to the major disruption incidents such as tsunamis, terrorist attacks, and economic crises (Tang, 2006). Disruption risks are rare events unlike the more common operational risks (Tang and Tomlin, 2008; Zhao et al., 2013). Internal risks arise within a supply chain network while external risks exist between a supply chain network and the environment (Goh et al., 2007). The more a firm relies on external sources, the more it is exposed to the outcomes of the other firms and the environment (Kull and Talluri, 2008).

Changes in business strategy are tailored to the type of supply chain risk (Christopher and Lee, 2004). Supply chain risk is usually assessed based on how they impact the performance variables such as cost, quality, delivery lead time, health, safety (Norrman and Jansson, 2004), information and cash flow (Chopra and Sodhi, 2004). In a broader context, supply chain risk is associated with equity risk and may have a negative impact on the long-term stock price and financial performance of a firm (Hendricks and Singhal, 2005).

Since the mid-twentieth century, organizations have expanded their focus on risk management, which were initially focused on the area of insurance management and is slowly shifting to supply chain issues (Kull and Talluri, 2008). We adopt the Tang (2006) definition on supply chain risk management as the tactics used to mitigate supply chain risk through the coordination or collaboration among supply chain partners to ensure profitability and continuity of the flows in the chain. There are 6 steps in conducting risk: risk identification, risk analysis, risk prioritization, risk characterization, risk reduction and risk monitoring (Eduljee, 2000; Van der Oost et al., 2003).

Holistic supply chain risk management is needed for a firm to gather information on the type of mitigation approaches to be applied based on different situational risks (Kull and Talluri, 2008). Thus, information from identification and assessment of supply chain risks is important for further risk management, as these are the two initial processes in risk management. Only with accurate risk assessment can effective risk mitigation be implemented.

The study of operational risks suggests that risk comprises three stages: ex-ante mechanisms as preventive strategies, in-process mechanisms for mitigation purposes, and ex-post mechanism for recovery from failures (Lewis, 2003). Supply chain risk evaluation can be considered as ex-ante mechanisms for risk prevention, whereas the management of supply, demand, product and information, as suggested by Tang (2006), can be classified as either in-process or out-process mechanisms for risk reduction. Overall, effective supply chain risk management is a risk prevention strategy, leading to a reduction in operational risks and supply chain vulnerability (Bogataj and Bogataj, 2007; Zhao et al., 2013).

2.5 Supply Based Risk

This study focuses on the risk exposure from cost, quality, delivery and flexibility in supplier evaluation for the following reasons: 1) All of these risk exposure criteria are the main competitive priorities in the purchasing function (Krause et al., 2001), 2) They persist in the supply chain literature (Tang and Tomlin, 2008) and 3) They are often cited as root causes of uncertainty from the perspective of customer demand (Trkman and McCormack, 2009). However, to evaluate the risk problems effectively, the understanding of supply risk sources is necessary. Table 2.1 summarizes the supply risk sources as well as their impact on the supply chain.

Supply chain risks that are associated with **cost** include the risk when the purchase cost is not competitive. This affects profitability (Krajewski and Ritzman, 2002). To be profitable under high purchase cost, a company may decide to post a higher sale price on their products. This decision may be costly as it may lead to more stocks and loss of market share (Xia and Chen, 2011). Therefore, cost related risks are important in supply risk management.

Product **quality** is measured on the process capability, performance design, durability, consistency and the continuous improvement of the product that meet customer specifications (Krause et al., 2001; Krajewski and Ritzman, 2002; Wang et al., 2012). A low quality product may lead to customer dissatisfaction, which may affect a firm's image (Xia and Chen, 2011). Customers may think twice before purchasing products from the same firm, which would make customer retention difficult. This affects the purchasing decision of the buyer. Moreover, poor quality not only accelerates product obsolescence, but also leads to additional cost in warranty and after-sale service (Xia and Chen, 2011) and unnecessary cost in the form of recalls (Zsidisin et al., 2004). For example, Firestone lost $2.1 billion when they had to recall 13 million tires which caused 203 deaths (Truett, 2001).

Delivery performance is explained in terms of how fast and how well customer orders are met with regard to the delivery time and quantity promises (Krause et al., 2001; Ting and Cho, 2008). Suppliers who are able to provide rapid and efficient delivery will outperform their competitors. Substandard delivery performance is a disruption in operation activities, and thus lowers the performance of the supply chain system (Yu et al., 2012).

Flexibility refers to the ability to meet customer needs by reacting quickly to the variability in demand and competitor moves (Gunasekaran et al., 2001). Flexibility on volume, new products and product mix, refer to a supplier's flexibility to make changes in volume, to introduce new products and address the needs of customers by developing or changing the designs and materials used in the product effectively (Krause et al., 2001; Kull and Talluri, 2008). The inability to make adjustments in volume and customizations within a specified time poses a risk in the form of delayed material flows in the supply chain (Chopra and Sodhi, 2004), which affects the profit margin. However, the different types of flexibility (e.g. volume, product modification, and product mix flexibility) placed on different products can lead to different impacts on the net profit, sales growth, and quality defect rates (Chang et al., 2006). Chang et al. (2006) reported that new product flexibility in the chip manufacturing industry in Taiwan leads to higher sales and profit, but with higher defective rates as well.

Table 2.1. Supply chain risks associated with cost, quality, delivery and flexibility

Criteria	Definition	Risk impact on supply chain
Cost		
Competitive pricing	Purchase price of the product	Increased inventory, loss of market share (Xia and Chen, 2011), decrease in profit margin (Krajewski and Ritzman, 2002)
Cost information	Supplier's willingness to share cost data	
Quality		
Product reliability	Consistent quality of the products	Reputation risk, reduction in loyal customers, unnecessary cost incurred (Xia and Chen, 2011)
Product durability	Durable products	
Conformance to specifications	Understand and conform to buyer specifications	
Delivery		
Expediting the ability	Willingness to expedite a rushed order	Disruption in operation activities (Yu et al., 2012), delay risk (Chopra and Sodhi, 2004), decrease in profit margin (Krajewski and Ritzman, 2002)
New product development time	Time taken for supplier to develop new product	
On time delivery	Meeting delivery promises on time	
Delivery speed	Supplier response to delivery order	
Delivery reliability	Consistently delivering products before promised due dates	
Flexibility		
Volume flexibility	Making changes in order volumes	Delay material flows (Chopra and Sodhi, 2004), impact on net profit, sales growth rate and quality defective rates (Chang et al., 2006)
Modification flexibility	Design new products or make design changes in existing products	
Mixed flexibility	Make changes on the mix of ordered items	

Source: Adapted from Krause et al. (2001)

Drawing as far back as the concept of sand cone model for the capability building in improving manufacturing strategy, a parallel is made to show that the four evaluation criteria in this case study (i.e. quality, cost, delivery and flexibility) can be further explained from this concept, which is presented in the following section.

2.5.1 Sand Cond Model

The concept of sand cone model from Ferdows and De Meyer (1990) is used in this study. The main purpose of this concept is to describe and rank the importance of multi-focused and multidimensional aspects of capability in improving the organization performance (see Figure 2.1), as well as achieving competitive edge in business . The "sand" stands for the management efforts and resources. As shown in Figure 2.1, quality is the most important capability to be improved first in order to create a stable foundation before one pursue to enhance other capabilities. By improving the foundation of each layer of quality, dependability and speed, the peak of cost efficiency can be finally achieved. In other words, the capability in developing a long term success for an organization depends on significant efforts placed in the earlier layers. In this study, we borrowed the concept of sand cone model and put it in the context of risk exposure.

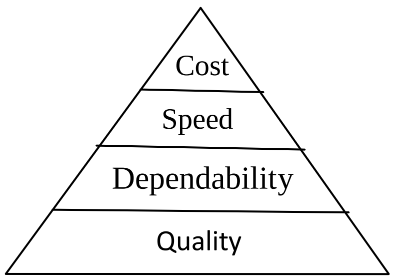

Figure 2.1. Sand cone model

2.6 Supplier Selection based MCDM Methodologies

In reviewing the methodologies used in this study, it was discovered that only a small number of studies applied DEMATEL and ANP decision approach in the context of supplier selection based risk factors. Thus, studies that employ MCDA decision methods are also covered in this literature review as the application area of those studies, supplier selection with the objective to evaluate the supplier's risk, is broadly similar to the objective in this study.

By using DEMATEL, Hsu et al. (2013) incorporated the carbon management concept in the context of supplier evaluation to determine the causal relationships and important weights of criteria so that carbon and climate change risks can be addressed effectively. On the other hand, Yucenur et al. (2011) employed FAHP and FANP to evaluate the global suppliers with respect to four main criteria: service quality, cost, risk factors and supplier characteristics. The risk factors included order delays, political stability, economy, customer complaints, geographical structure, terrorism, climate conditions and cultural differences. The results revealed that although both approaches have the same ranking of suppliers, the evaluation criteria were differently ranked.

Talluri et al. (2006) proposed a chance constrained data envelopment analysis (CCDEA) approach for vendor selection under supply risk. They considered a performance variability problem in supplier attributes with price as an input and quality and delivery as outputs. Wu and Olson (2008) compared data envelopment analysis (DEA) with other multi risk assessment approaches such as chance constrained programming (CCP) and MOP in evaluating the performance of 10 vendors based on expected cost, quality acceptance levels, and on-time delivery distributions. The results obtained were then compared with simulation models and analysis showed that the models' produced results were consistent with each other. Recently, Wu et al. (2013) commented that the DEA method proposed by Talluri et al. (2006) may result in sub-optimal solutions since only a single objective function was considered. Moreover, a DEA approach is limited when evaluating the imprecise and ambiguity of the risk measures.

To deal with imprecise and vague data, a conceptual framework such as the fuzzy set analysis proposed by Zadeh (1965) is needed in risk evaluation (Kangari and Riggs, 1989). For instance, Azadeh and Alem (2010) compared the simulation approaches of fuzzy DEA, DEA and CCDEA for supply chain risk and supplier selection under three conditions: uncertainty, certainty, and probabilistic. Furthermore, uncertainty can be also modeled by simulation and stochastic concepts. Olson and Wu (2011) demonstrated how DEA, simulation DEA and Monte Carlo simulation can be used as appropriate tools for outsourcing evaluation under risk adjusted cost concept in a supply chain. Simulation analysis was used to compare the expected performance of vendors in uncertainties after dominated and non-dominated partners identified by DEA.

To address the subjective information, other more flexible approaches have been explored in supplier evaluation under risk. For example, Wu et al. (2006) proposed an AHP to analyze and compare the ranking of 18 inbound supply risk factors for two suppliers with respect to internal controllable, internal partially controllable, external partial controllable and external uncontrollable risks. However, all of these analytical approaches assumed that the risk criteria are independent of each other and ignored the interaction and interdependency relationships between the criteria.

In supplier selection, the purchasing manager must not only decide which suppliers to be contracted, but also determine the quantity to be allocated among the suppliers (Weber and Current, 1993). Thus, the literature also focuses on supplier risk performance that deals with the multi-objective decision making approaches. Kull and Talluri (2008) have constructed AHP and goal programming approaches in supplier selection by taking into account supply risk and product life cycle. They proposed 18 sub-criteria under five key risk criteria: cost failure, quality failure, delivery failure, flexibility failure, and confidence failure. However, since they did not consider interaction effects between the criteria, Kull and Talluri (2008) recommended the use of ANP to consider such effects.

Wu et al. (2010) formulated a supplier selection model using a possibility FMOP, with quantitative and qualitative risk criteria. The quantitative risk criteria included cost, quality and on-time delivery, while the qualitative risk criteria included vendor performance and economic environment. Recently, Wu et al. (2013) proposed stochastic, fuzzy and possibilistic programming to solve the three levels of supply chain outsourcing risk management. More recently, FMOP methodology has attempted to model and investigate the effects of joint supply chain risk and supply chain visibility in supply chain performance. By assuming three equally weighted objective functions of cost, supply chain visibility and risk, Yu and Goh (2014) modified Amid et al.'s (2006) fuzzy multi-objective approach for the supplier selection of car lock systems. However, these studies ignored the interdependent relationships that exist in deriving the weights of the objective functions. Table 2.2 summarizes the above literature by arranging the papers according to their year of publication.

An integrated method of DEMATEL and ANP is used to solve the complex, interactive, feedback relationships among the criteria, and to construct the importance weights of the criteria (Hsu et al., 2013; Chen and Chen, 2013). In addition, this hybrid method has been used in various applications such as air transport management (Liou et al., 2007; Liou, 2012; Hsu and Liou, 2013), construction and civil engineering (Huang et al., 2014; Liu et al., 2014; zhou et al., 2014), environmental management (Tseng, 2011), education (Tseng, 2010),