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Data-driven risk management in supplier selection for the Turkish textile industry

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Data-driven Risk Management in Supplier Selection for the Turkish Textile Industry

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DECLARATION

I, Alptekin Ulutas, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Australia, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

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PUBLICATIONS

Some of the content presented in this thesis has been included in the following publications:

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1. Ulutas, A., Shukla, N., Kiridena, S. & Gibson, P. (in press). A Utility-driven Approach to Supplier Evaluation and Selection: Empirical Validation of an Integrated Solution Framework. *International Journal of Production Research*.

2. Ulutas, A., Kiridena, S., Gibson, P. & Shukla, N. 2012. A novel integrated model to measure supplier performance considering qualitative and quantitative criteria used in the supplier selection process. *International Journal of Logistics and SCM Systems*, 6, 57-70.

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EXTENDED ABSTRACT

In light of the major shifts in customer preferences, competitive dynamics and certain organisational practices witnessed in recent times, many studies have highlighted the strategic significance of supplier evaluation and selection (SES) decisions. For instance, constantly changing customer requirements, increasing levels of globalisation and growing trends in outsourcing have all made organisations heavily reliant on their suppliers and this has increased the need to become more diligent in the selection of suppliers. In terms of improving organisational performance, SES decisions can play a critical role in reducing overall purchasing costs, as well as maintaining satisfactory delivery lead times and quality standards.

Over a long period of time, researchers have studied the SES problem from a variety of perspectives and proposed wide range of frameworks and models to support SES decisions. Despite many and varied models currently available and ongoing efforts to refine existing solution frameworks, the literature points to a lack of efficacy of the existing SES models. Among the major criticisms found in the literature are: the limited capacity of the available approaches to deal with uncertainty and the risks associated with supplier performance; lack of agreement on the criteria to be used in the initial screening stage and lack of feasibility and relevance of the most advanced models that have been proposed. SES decisions, in particular, can be affected by typical supply chain risks, such as the volatilities in demand, uncertainties related to economic conditions and disruptions caused by a range of human-induced actions, as well as naturally occurring events. The majority of existing models, however, do not have the capacity to solve these problems. It is, therefore, imperative that renewed efforts should be directed toward the development of new solution frameworks which will be successful.

Considering the evolving nature of the SES problem and the deficiencies of existing models, this thesis presents an integrated model developed by synthesising state-of-the art evaluation and order allocation techniques in order to support SES decisions. This integrated model provides solutions to the key problems identified in the literature review. It is capable of handling both the quantitative and the qualitative criteria used in supplier evaluation. It can comprehensively take account of a range of performance features and other attributes of potential suppliers. It is also simple and efficient for practitioners to use.

The proposed integrated model consists of two mathematical models aimed at mitigating the capability-based and performance-based risks associated with SES decisions. These two mathematical models, namely the fuzzy integrated model (FIM) and the fuzzy stochastic integrated model (FSIM), were developed based on a critical evaluation of the existing array of tools and techniques for their suitability to address the key difficulties identified above. The FIM makes use of a fuzzy analytic hierarchy process (FAHP) to assign weights for qualitative criteria/objective functions. It uses fuzzy complex proportional assessment (COPRAS-F) to evaluate supplier capability with respect to capability-based risks. It makes use of the signed distance method to convert fuzzy numbers into crisp numbers. Finally, it uses fuzzy linear programming (FLP) to solve the overall problem of supplier selection and order allocation using the max-min method. The FIM was validated using empirical data drawn from eight Turkish textile companies with respect to solving their SES problems.

The results of the FIM confirmed that the companies participated in this study would have benefitted from using the FIM in terms of savings in purchasing costs, improved delivery times and reductions in the numbers of defective items delivered. For example, if Company A’s purchased order quantities had been generated using the FIM,

it would have been able to save 6.9 % of the total purchasing costs and could have reduced the number of late delivered units by 22.6% and defective units by 21.5 %. Similarly, Company B would have saved 2.5 % of the total purchasing costs while achieving improvements of 3.7% in delayed units and 4.4% in defective units. The other companies would have achieved comparable savings in purchasing costs with the highest proportion of savings amounting to 12.1 % of total purchasing costs achieved by Company C. Additionally, the application of the FIM in Company G resulted in a reduction of 39.5% in the number of delayed units. The greatest reduction in defective units delivered (21.5%) by using the proposed model was achieved by Company A. Thus, the efficacy and superiority of the proposed FIM was confirmed through the results of its application in all eight Turkish textile companies.

Additionally, the FIM was compared with possibilistic integrated model (PIM) including FAHP, FTOPSIS and possibilistic linear programming (PLP) to test effectiveness of the FIM. The FIM and the PIM are used to solve SES problem for only one company (i.e. Company D). First of all, the results of FTOPSIS and COPRAS-F will be compared to test the effectiveness of COPRAS-F. The performance of COPRAS-F is better than the performance of FTOPSIS in terms of results of these two models. Moreover, PLP and FLP were compared to test effectiveness of the FLP. The results of PLP are $13,112,500 cost, 425,500 late delivered units and 86,883 defective units. The results of FLP are $13,000,000 cost, 425,000 late delivered units and 84,500 defective units. It can be seen that if PLP were used to solve SES problem for Company D, it would have been able to renounce $112,500 (out of $ 13,000,000) of the total purchasing cost and it would have been able to purchase 500(out of 425,000) more late delivered units and 2,383 (out of 84,500) more defective units. It can be said that the

FIM, which was used to solve SES problem in this thesis, is more effective than the PIM.

The FSIM utilises FAHP, COPRAS-F and fuzzy stochastic goal programming (FSGP) to mitigate capability-based and performance-based risks. The functions of the FAHP and COPRAS-F are the same as in the FIM but they are used to reduce the number of suppliers to a manageable level (pre-selection phase) in the FSIM, before using FSGP to mitigate capability-based and performance-based risks. This model is verified with the help of two numerical examples representing different purchasing situations. In the first example, the FSIM considers single-item, multiple-period and multiple-transportation options to solve the SES problem under quantity discount conditions. In the second example, the FSIM considers multiple item, period and transportation options to solve the SES problem under bundling discount conditions.

The results obtained through the above applications demonstrate the capacity of the proposed model to deliver better outcomes concerning the selection of preferred suppliers, as well as the allocation of orders to those suppliers. The performance-related outcomes include reduced overall purchasing costs, better delivery performance and fewer defective items. It was also shown that the proposed model can provide the flexibility required in accounting for a number of situational factors applicable to SES decisions.

Future research that could be undertaken following the approach proposed in this thesis includes: adapting the proposed model to account for disruption risks, preferably through the addition of a suitable objective function; further validation of the proposed model through applications in other domains such as services and the public sector, as well as extending the two constituent modules to account for other buying situations such as multiple buyers and/or multiple suppliers.

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GLOSSARY

SES	**S**upplier **E**valuation and **S**election
FIM	**F**uzzy **I**ntegrated **M**odel
FSIM	**F**uzzy **S**tochastic **I**ntegrated **M**odel
FAHP	**F**uzzy **A**nalytic **H**ierarchy **P**rocess
COPRAS-F	**F**uzzy **CO**mplex **PR**oportional **AS**sessment
FLP	**F**uzzy **L**inear **P**rogramming
FSGP	**F**uzzy **S**tochastic **G**oal **P**rogramming
DMs	**D**ecision-**M**aker**S**
FST	**F**uzzy **S**et **T**heory
AHP	**A**nalytic **H**ierarchy **P**rocess
ANP	**A**nalytic **N**etwork **P**rocess
ELECTRE	**EL**imination and **C**hoice **E**xpressing the **RE**ality
PROMETHEE	**P**reference **R**anking **O**rganisation **METH**od for **E**nrichment **E**valuations
TOPSIS	**T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution
VIKOR	Multi-Criteria Optimisation And Compromise Solution
SMART	The **S**imple **M**ulti-**A**ttribute **R**ating **T**echnique
DEMATEL	The **DE**cision-**MA**king **T**rial and **E**valuation **L**aboratory
GRA	**G**rey **R**elational **A**nalysis
MPMs	**M**athematical **P**rogramming **M**ethods
LP	**L**inear **P**rogramming
ILP	**I**nteger **L**inear **P**rogramming
MILP	**M**ixed-**I**nteger **L**inear **P**rogramming
NP	**N**onlinear **P**rogramming
MINLP	**M**ixed **I**nteger **N**onlinear **P**rogramming
GP	**G**oal **P**rogramming
DEA	**D**ata **E**nvelopment **A**nalysis
MOP	**M**ulti-**O**bjective **P**rogramming
TCO	**T**otal **C**ost of **O**wnership
AIMs	**A**rtificial **I**ntelligence **M**odels
GAs/GA	**G**enetic **A**lgorithms/**G**enetic **A**lgorithm
NN	**N**eural **N**etworks
PSOs	**P**article **S**warm **O**ptimisations
ACA	**A**nt **C**olony **A**lgorithm
ESs	**E**xpert **S**ystems
CBR	**C**ase-**B**ased **R**easoning
BN	**B**ayesian **N**etworks
GST	**G**rey **S**ystem **T**heory
RST	**R**ough **S**et **T**heory
DST	**D**empster-**S**hafer **T**heory
AR	**A**ssociation **R**ule
SVM	**S**upport **V**ector **M**achine
DT	**D**ecision **T**ree
AI	**A**rtificial **I**ntelligence
PCA	**P**rincipal **C**omponent **A**nalysis

FA	**F**actor **A**nalysis
SEM	**S**tructural **E**quation **M**odelling
ISM	**I**nterpretive **S**tructural **M**odelling
BOCR	**B**enefits, **O**pportunities, **C**ost and **R**isks
DSCP	**D**eveloping the **S**election **C**riteria **P**hase
FSP	**F**inal **S**election **P**hase
FTOPSIS	**F**uzzy **TOPSIS**
DEAHP	**D**ata **E**nvelopment **A**nalytical **H**ierarchy **P**rocess
QFD	**Q**uality **F**unction **D**eployment
FANP	**F**uzzy **A**nalytic **N**etwork **P**rocess
MCGP	**M**ulti-**C**hoice **G**oal **P**rogramming
MCDM	**M**ulti **C**riteria **D**ecision-making **M**odel
SWOT	**S**trengths, **W**eaknesses, **O**pportunities, **T**hreats
CCP	**C**hance-**C**onstrained **P**rogramming
CCDEA	**C**hance **C**onstraint **DEA**
TS	**T**abu **S**earch
Fuzzy MP	**F**uzzy **M**athematical **P**rogramming
Stochastic MP	**S**tochastic **M**athematical **P**rogramming
FGP	**F**uzzy **GP**
SAW	**S**imple **A**dditive **W**eighting
FMCGP	**F**uzzy **MCGP**
PLP	**P**ossibilistic **L**inear **P**rogramming
CCLP	**C**hance **C**onstrained **L**inear **P**rogramming
TFNs	**T**riangular **F**uzzy **N**umbers
GDP	**G**ross **D**omestic **P**roduct
EU	**E**uropean **U**nion
CFOs/CFO	**C**hief **F**inancial **O**fficers/**C**hief **F**inancial **O**fficer
CRM	**C**ustomer **R**elationship **M**anager
COO	**C**hief **O**perating **O**fficer
HRM	**H**uman **R**esource **M**anager
PIM	**P**ossibilistic **I**ntegrated **M**odel
LTL	**L**ess-than-**T**ruck-**L**oad

1 INTRODUCTION

1.1 Background

A typical supply chain consists of a series of business activities either directly or indirectly contributing to achieving the desired flow of goods, services, information, money and knowledge in order to satisfy end-user needs. Hence, the success of any supply chain depends on the effective management of the above mentioned flows from their source through to the final customers.

Supply chain management employs numerous approaches, tools and techniques to integrate suppliers, manufacturers, warehouses and retail stores in order to effectively manage these flows. The overarching goal is to ensure that the right quantities of products (or services) are delivered to the right locations at the right time, thus minimising the chain-wide costs while also fulfilling the service-level requirements and maximising total supply chain profitability (Simchi-Levi et al., 2003; Chopra and Meindl, 2004). Some of the major challenges associated with managing these flows are: achieving the levels of visibility required to facilitate coordination between supply chain partners; managing risks and uncertainties around supply, demand and quality parameters; and minimising delivery lead times and delays while minimising chain-wide costs (Simchi-Levi et al., 2003; Butner, 2010; Abbasi and Nilsson, 2012; Bala, 2014).

Amongst the major approaches used in managing the risks associated with the supply-side operations of a supply chain is supplier selection and evaluation (Simchi-Levi et al., 2003; Chopra and Meindl, 2004; Leenders, 2006; Lysons and Farrington, 2006). Additionally, supplier selection can have direct implications for maintaining satisfactory delivery lead times, quality standards and costs.

Supplier evaluation and selection (SES) has long been recognised as an important and integral part of core supply chain management functions. In recent times, the strategic significance of SES decisions has become even greater in light of major shifts in customer preferences, competitive dynamics and certain organisational practices. For instance, constantly changing customer requirements, increasing levels of globalisation and outsourcing have made organisations heavily reliant on their suppliers, and this has increased the need to become more diligent in the selection of suppliers. Apart from the need for dealing with the impact of these global trends, SES decisions have always been critical in terms of reducing material costs, mitigating purchasing risks, ensuring product quality and improving delivery performance, all of which directly contribute to enhancing supply chain performance, as well as organisational competitiveness (De Boer et al., 2001; Monczka et al., 2005; Lee and Ou-Yang, 2009; Sarkar and Mohapatra, 2009; Sanayei et al., 2010; Liao and Kao, 2011).

SES has traditionally been treated as a multi-criterion decision-making problem with both qualitative and quantitative dimensions. The quantitative criteria, in general, deal with aspects of supplier performance that can be measured objectively: for example, cost/price, lead time and the percentage of defective items delivered. In contrast, qualitative criteria deal with supplier attributes that cannot be readily quantified, for example operational practices, organisational capabilities and the capacity to assimilate new technology. Additionally, there are other considerations deemed important in selecting potential suppliers, for example, the alignment of strategic goals, mutual trust and potential for collaboration between buyers and suppliers. Accounting for all these aspects comprehensively is expected to ensure a mutually beneficial long-term relationship between the buyers and suppliers involved, while at the same time delivering on the requirements and expectations of the end user.

However, there are a number of other factors in a typical business environment that impact on the efficacy of supplier selection decisions, for example, the volatilities in demand, uncertainties relating to economic conditions and disruptions caused by both man-made and natural disasters. All these factors pose significant and ongoing challenges for researchers in their quest for satisfactory solutions to the SES problem.

Despite many and varied solutions that have been proposed, and the ongoing efforts to refine existing solution frameworks, the supply chain management community seems to be not content with the efficacy of the existing SES models. Major criticisms found in the literature include: the limited capacity of the available approaches to deal with uncertainty and the risks associated with supplier performance; lack of agreement on the criteria (particularly qualitative criteria) to be used in the initial screening stage; and lack of feasibility and relevance of the most advanced frameworks that have been proposed (De Boer et al., 2001; Bilsel, 2009; Jain et al., 2009). It is, therefore, imperative that renewed efforts be directed toward the development of new solution frameworks which address these issues.

Considering the evolving nature of the SES problem and the current status of research in this area, as outlined above, this thesis presents a novel and holistic solution two-module integrated model developed by synthesising state-of-the art evaluation and order allocation techniques/algorithms. The proposed two-module integrated model addresses some of the issues outlined above in that: it is capable of handling both quantitative and qualitative criteria; it can comprehensively take account of a range of performance features and other attributes of potential suppliers; and it is simple and efficient for practitioners to use.

The SES problem has been extensively studied from a variety of perspectives. The level of outsourcing, global sourcing and uncertainty in decision-making have been

identified in the literature as major issues driving the current research efforts in SES (De Boer et al., 2001; Chan and Kumar, 2007; Bilsel and Ravindran, 2011).

In general, the typical SES process consists of six stages: (i) identifying the need to select (or rationalise) suppliers and exploring possible options; (ii) identifying the desired attributes of potential suppliers, considering the strategic priorities of the buyer organisation and developing the criteria (metrics) for evaluating potential suppliers; (iii) screening potential suppliers for their alignment with strategic priorities; (iv) evaluating a shortlisted set of candidate suppliers against the metrics developed in step (ii); (v) allocating orders to preferred suppliers, considering their production capacity and suitability to fulfil required orders; and (vi) ongoing monitoring of supplier-buyer relationships and supplier performance against the terms of the contract (De Boer et al., 2001; Sonmez, 2006; Aissaoui et al., 2007). The treatment of the SES problem in this thesis is such that it only deals with steps (ii) through (v) of the SES process outlined above. In comparison with previous research efforts in this area, this study attempts to solve the SES problem with particular attention to dealing with supply chain risks and the variability associated with the performance of suppliers. Additionally, it considers the imprecise nature of information available to the decision maker for solving the SES problem, as well as a number of other contextual factors that influence SES decisions.

This introductory chapter is organised as follows. Section 1.2 articulates the overall research problem. Section 1.3 identifies the research questions which this study aims to address. Section 1.4 discusses the significance of research findings derived from the study. Section 1.5 presents the scope of this study as determined by the research questions identified above. Section 1.6 provides an abridged account of the research design and methodology employed in this study. Section 1.7 acknowledges the limitations of this study followed by a thesis outline in Section 1.8.

1.2 Research Problem

Risk and uncertainty, which have become part and parcel of every supply chain operating in a global environment, can have a significant impact on the short-term and long-term performance and success of all partner entities (Simchi-Levi et al., 2003; Mendoza, 2007). On the one hand, uncertainty can often stem from a lack of or absence of information and knowledge associated with certain decision environments (Rowe, 1977; Brindley and Ritchie, 2004). On the other hand, risk is defined as the probability of exposed losses (Knight, 1921; Brindley and Ritchie, 2004). As such, the key difference between risk and uncertainty is that in risk, the probability of possible outcomes associated with the event concerned is known (Tversky and Kahneman, 1992; Zinn, 2004), whereas in dealing with uncertainty the nature and probability of possible outcomes are considered unknown (Williams and Baláž, 2012). The impacts of uncertainties and disruptions are, in general, treated as supply chain risks. Supply chain risks, in turn, can be divided into operational risks and disruption risks (Kleindorfer and Saad, 2005; Tang, 2006; Chopra et al., 2007; Bilsel and Ravindran, 2011). The sources of operational risks affecting the performance of suppliers include regularly occurring uncertainties such as demand fluctuations and transport delays (Tang, 2006; Bilsel, 2009; Bilsel and Ravindran, 2011), whereas those of disruption risks may be rare events such as natural disasters or industrial actions (Kleindorfer and Saad, 2005). Several studies have considered risks in the SES process, but these studies have not comprehensively examined operational risks (Bilsel, 2009; Bilsel and Ravindran, 2011; Li and Zabinsky, 2011). For instance, most studies have analysed typical uncertainties, such as variability in total cost, production capacity, late delivery percentage, defect percentage and order requirements, but have left out risks induced by intangible attributes such as lack of supplier capabilities (see Table 1.1). Therefore, there is a need

to deal with these ‘capability-based risks’ more comprehensively to mitigate their impact on the SES process. Capability-based risks can be defined as supplier’s potential risks that negatively affect the buyer company for a long term period. Therefore, capability-based risks considered in this study include supplier attributes such as financial position, volume flexibility, technological capability, reputation, compliance with sectoral price and communication issues and these attributes are intangible, which are difficult to quantify (Barbarosoglu and Yazgaç, 1997; Chan, 2003; Sarkar and Mohapatra, 2006; Chan and Kumar, 2007; Çifçi and Büyüközkan, 2011; Punniyamoorthy et al., 2011). The effect of this type of risks can be observed in long period. For example, if financial position of supplier is not good in market, the buyer company purchasing items from this supplier can face with the risk of supplier bankruptcy and financial distress in long term. Additionally, the low of volume flexibility can affect the buyer company in terms of delaying delivery and, the buyer company may work with another supplier to meet its order requirement; that is, the buyer company may pay extra money for purchasing. Technological incapability of suppliers can cause increasing of the late delivered and defective items to the buyer company. Additionally, the buyer company could fall behind its global competitors in terms of the development of product design. Bad reputation of supplier in market can affect the image of manufacturer in market badly and bad reputation can reduce the reliability of manufacturer to the supplier. This can negatively affect long term relationship between supplier and manufacturer. Moreover; if the supplier’s sale price of items is above the sectoral price in market, manufacturer can purchase items expensively. This can cause increasing of purchasing cost of the buyer company. Additionally, communication issues can affect delivery time and purchased quantity of items badly. Therefore, the buyer company can fall behind its order schedule due to

communication issues in long term. Performance-based risks can be defined as the variability in the demonstrated ability of suppliers that negatively affect the short term goals of the buyer company. Therefore, performance-based risks considered in this study include supplier performance attributes, such as uncertain cost, late delivery percentages, defect percentages and order requirements as well as supplier production capacity and these attributes are tangible (Bilsel, 2009; Wu et al., 2010; Bilsel and Ravindran, 2011). This type of risks can be faced regularly and these risks can push the manufacturer to change order schedule and increase the purchasing cost. For instance, the supplier's sale price of items can easily vary in short term because of daily changing of exchange currency rate and inflation rate. This can push manufacturer to increase money for payment of purchasing items, and this can cause changing of short term goals of the buyer company. Moreover, the number of late delivered items can vary daily due to weather conditions and traffic problems, and this can force the buyer company to change order schedule of production in short term. Additionally, the number of defective items can change regularly because of increasing of the faulty of workmanship. When the manufacturer faces with this problem, it can pay extra money to complete its order in short term. Furthermore, the order requirement of the manufacturer can vary in short period due to changing customer preferences, and this can force the manufacturer to change order schedule of production in short period. The changing of order schedule can bring the increase of purchasing cost. Besides, as production capacity of supplier can vary in short period because of instability of machine and labour performance, manufacturer can face with the risk of working with stockless. In addition, manufacturer cannot meet its order requirement; therefore, customer of this company cannot satisfy the service of the manufacturer. Operational risks considered in this study consist of capability-based including qualitative data and

affecting the manufacturer in long term and performance-based risks including quantitative data and affecting the manufacturer in short term (Sarkar and Mohapatra, 2006; Bilsel, 2009; Bilsel and Ravindran, 2011). Therefore, both capability-based (qualitative) and performance-based (quantitative) risks will be considered in this study to reduce negative effects of these risks for short and long period. The choices made in relation to the treatment of risks associated with supplier selection in this study are illustrated in Table 1.1 below.

Table 1.1: The scope of the study

Risks / **Data**	**Operational Risks (Considered in this thesis)**	**Disruption Risks**
Quantitative	Performance-Based Risks • uncertain order requirements • uncertain total cost • uncertain production capacity • uncertain late delivery percentage • uncertain defect percentage	Resilience (e.g. terrorism, natural disasters)
Qualitative	Capability-Based Risks • financial position of supplier • volume flexibility • technological capability • reputation • compliance with sectoral price • communication issues	Robustness (e.g. economic instability, political instability)

A number of previous studies have made useful contributions to solve the SES problem, considering the uncertainty induced by imprecise data associated with supplier performance. Building on those contributions, this study employs techniques capable of dealing with imprecise data to mitigate both performance-based and capability-based risks. Accordingly, imprecise data is dealt with in three different forms: qualitative

(linguistic) data, fuzzy data and stochastic (quantitative) data. Several previous studies which have examined the SES problem have also considered qualitative, fuzzy and stochastic data individually to mitigate the effects of uncertainty. Even though these studies have presented useful approaches/models for solving the SES problem, the types of imprecise data obtained may still change with respect to the nature of the decision environment. For example, suppliers and buyer companies may provide both fuzzy and stochastic data. Therefore, a more comprehensive model including qualitative, fuzzy and stochastic data is required to address the SES problem. Moreover, transportation costs are an important part of purchasing costs considered within the SES process, particularly given the increasing levels of global sourcing. Transportation alternatives applicable to a given supply arrangement may affect transportation costs, and hence product costs, as well as other secondary considerations such as carbon emissions (not discussed in this thesis). In the literature, there are only a few studies that have considered transportation alternatives when addressing the SES problem. Therefore, there is an opportunity for considering transportation alternatives in developing a more comprehensive solution to the SES problem. Additionally, suppliers may offer discounts depending upon the size/quantity of the order placed. Most of the existing literature does not consider discounts, especially bundling discounts, which are a special type of discount given for purchasing two or more items from the same supplier. This can also be incorporated into a more comprehensive SES model.

The SES problem has been researched from a wide range of perspectives over a long period of time and there exists a plethora of models, methods and techniques to support SES decisions. However, the changing nature of the business environment and the increasing attention paid to SES mean there is a need for continuing efforts towards developing more effective and efficient decision support frameworks. Moreover, the

growing array of models proposed in the literature has rarely been subject to empirical validation although there have been several publications examining the usefulness of systematic and comprehensive methods for evaluating and selecting suppliers. This lack of diffusion of SES models in the industry is partly due to the proliferation of models and techniques that have not been subject to empirical validation. In summary, the literature review undertaken as part of this study indicates that there is a clear need for developing more comprehensive and practitioner-oriented frameworks and models to support SES decisions.

1.3 Research Questions

Considering the overall research problem outlined in the previous section, and the limitations of the existing SES models identified through the literature review, this thesis was designed to examine the following research question:

- How can operational risks associated with supplier selection be mitigated through the development and validation of a more comprehensive SES model that accounts for multiple situational factors?

The challenge of addressing this primary research question is approached from a number of perspectives incorporating the following dimensions:

– addressing the need for evaluating the requisite qualitative and quantitative attributes of candidate suppliers using a combination of suitable methods;

– accounting for multiple situational factors such as single vs. multiple items, single vs. multiple periods and various forms of discounts that affect supplier selection decisions using a two-module integrated model; and,

– empirically validating the first module of the proposed integrated model using data drawn from a sample of organisations in the Turkish textile industry.

Given the large number and diversity of research issues identified through the literature review, and the need to develop a SES model that demonstrates a high degree of utility, there was a choice to be made in relation to what research issues to address in this study, and what research issues to leave to future research. As such, in formulating the above research question had to be exercised concerning the trade-offs involved in prioritising the research issues. Further details about the approach followed in this regard are elaborated in the methodology section (see Section 1.6).

1.4 Significance of this Research Study and its Findings

The benefits of adopting a systematic approach to supplier selection have been widely reported in the literature. As indicated in Section 1.1, purchasing is a major source (or driver) of supply chain costs. Therefore, there is an immediate opportunity to reduce product costs across the supply chain through careful selection of suppliers. Additionally, engaging or partnering with suitable suppliers enables the buyer organisation to reduce product development time, improve product quality and reduce delivery lead time. Moreover, comprehensive evaluation of potential suppliers may help achieve better coordination and integration between suppliers and buyers to reduce inventory levels and better align supply and demand (Simchi-Levi et al., 2003; Chopra and Meindl, 2004). Ordering and production schedules may also be optimised through the selection of suppliers with matching operations systems and production capacities. For instance, the numbers of late delivered units and defective units may be reduced through partnering with suitable suppliers to improve the dependability of ordering and production schedules. More importantly, a well-developed approach to supplier selection may allow the buyer organisation to share risks with reliable and responsible suppliers. Overall, through collaborative win-win type relationships, both buyer

organisations and suppliers can leverage their core competencies for competitive advantage while sharing risks, resources and capacity across the supply chain.

This study proposes an integrated SES model that helps decision-makers, in their evaluation of potential suppliers, to take account of a range of factors and circumstances, which will lead to the selection of suppliers whose performances and capabilities better match with the buyer's requirements. The model also addresses a number of limitations of existing models as outlined in Section 1.2. However, the most significant advantage of the integrated model is its capacity to deal with the variability associated with supplier performance and capability attributes. This will contribute to mitigating the risks in supplier selection. The other benefits of the integrated model include: its comprehensiveness in terms of being able to deal with a range of situational factors pertaining to supplier selection decisions; its ability to account for quantitative and qualitative data concurrently; and its veracity and efficacy, verified by numerical, as well as empirical, data and practitioner evaluations. As such, the integrated model is expected to serve as a useful decision support tool for supply chain practitioners in dealing with the SES problem. Besides, this model has a degree of flexibility built into it. On the one hand, it consists of two modules; one utilising fuzzy methods and the other utilising fuzzy and stochastic methods. On the other hand, the two sets of methods used at both screening and evaluation stages of the model are such that individual criteria can be expanded or replaced to suit varying applications and priorities, for example, to account for environmental factors and to accommodate individual or group decision-making. This allows for catering to varying degrees of decision-making complexity and situational demands presented by different industry contexts, without having to develop a radically new model. Therefore, with further empirical support

through future research, there is potential for this model to be adapted to suit different application domains.

1.5 Scope of the Study

This study focuses on the analysis of performance-based and capability-based operational risks with a view to improving the supplier selection process (see Table 1.1). However, its scope is limited to dealing with operational risks. This was a deliberate choice, driven primarily by the constraints imposed by time and resources, including limited access to data. The prioritisation of operational risks over disruption risks were based on the assumption that the probability of disruption risks is low and these are due to unpredictable events, such as earthquakes, floods and terrorism, and the data for such events is difficult to acquire. The analysis of the effects of disruption risks in SES literature was found to be limited, the analysis of such risks may require substantial data, resources as well as substantially different set of techniques, and this would have acted as a major barrier to the successful completion of this study. Moreover, Turkish textile companies, which participated in this study, explained that they do not consider disruption risks in the supplier selection process. Additionally, the impact of disruption risks may vary substantially with respect to the geographical location of suppliers. For example, some suppliers may be located in earthquake zones and therefore face heightened levels of earthquake risk, whereas other suppliers may be located in flood areas and face with higher levels of flood risk. These variations may also pose further challenges in terms of the development of a comprehensive model as envisaged in this study.

Additionally, green supplier selection criteria, such as carbon emission levels, waste reduction, recycling and reuse, have not been taken into account in the criteria included in the model. This was partly driven by the initial feedback received from the

Turkish textile companies, which participated in this study to the effect that such criteria were not considered when selecting suppliers. Moreover, as indicated in Section 1.4, the proposed module can accommodate additional criteria to suit varying contexts with little or no adjustment to the structure and of the model, and therefore including an exhaustive list of criteria was not considered a priority.

1.6 Research Design and Methodology

This section outlines the research design and methodology employed in addressing the key research question identified in Section 1.3. As such, it provides a summary account of the process followed in developing the conceptual framework that guided this study, and of the development of the proposed first module of the integrated model and its validation, including data collection and analysis.

1.6.1 Theoretical Foundation

The research problem in this study was developed based on a comprehensive review of the literature, covering the studies that have attempted to address issues associated with solving the SES problem in general, and the treatment of risks associated with supplier selection in particular. The issues associated with solving the SES problem have been many and varied, as has been outlined in Sections 1.2 through 1.4. The treatment of risks in supplier selection has primarily been addressed using fuzzy mathematical programing models with much fewer efforts focusing on fuzzy stochastic programming approaches. Given the diversity of research issues cited in the extant literature, this study recognised the need for developing a SES model that could comprehensively deal with the operational risks in supplier selection while addressing as many limitations of the existing models as possible.

1.6.2 Model Development

In the first module of the proposed integrated model, which is called fuzzy integrated model (FIM), the fuzzy analytic hierarchy process (FAHP) and fuzzy complex proportional assessment (COPRAS-F) are used to evaluate suppliers with respect to capability-based risks (qualitative criteria). FAHP is used to determine the relative weights of the defined qualitative criteria. COPRAS-F is used to produce a set of scores which rank the suppliers according to a set of qualitative criteria. The resultant aggregate weighted scores (representing all qualitative criteria) are used as objective function coefficients in the fuzzy linear programming (FLP) model.

Performance-based risks (quantitative criteria) are measured using fuzzy numbers. These fuzzy numbers are converted into crisp numbers using the signed distance method so that they can be used in the FLP model in the form of weights for the objective functions and constraint (supplier production capacity).

FAHP is employed again to identify the relative weights of all objective functions used (minimisation of total purchasing cost; minimisation of the number of units delivered late, minimisation of the number of defective units and maximisation of total score). This FLP model is used to solve the problem of supplier selection and order allocation using the max-min method. The fuzzy integrated model (FIM) has been verified using numerical examples. Numerical examples for verification have not been included in this thesis, as the feasibility and superiority of this model have been proved by empirical data (see Chapter 4).

The fuzzy integrated model (FIM) described above does not consider several situational factors that affect SES decisions, such as multiple items, multiple periods, multiple transportation alternatives and discounts. Therefore, a second module called the fuzzy stochastic integrated model (FSIM) has been proposed to account for

single/multiple item(s), multiple periods, multiple transportation alternatives and discounts. In FSIM, FAHP and COPRAS-F were used in the manner described above. In contrast, in the second module FAHP and COPRAS-F are used to reduce the number of suppliers to a manageable level (pre-selection) and the resultant aggregate weighted scores for the shortlisted suppliers are used as objective function coefficients in the fuzzy stochastic goal programming (FSGP) model. Then, fuzzy coefficients of each objective functions (uncertain cost, late delivery percentage and defect percentage) are converted into crisp coefficients. FAHP is used to identify the weights of the objective functions (minimisation of total purchasing cost; minimisation of the number of units delivered late, minimisation of the number of defective units and maximisation of total score). Objective functions and stochastic constraints (supplier production capacity and order requirements) are analysed together to select the preferred suppliers and allocate orders among these suppliers. The FSIM is verified using two numerical examples. In the first example, the FSIM considers a single item, multiple periods, multiple transportation alternatives and price discounts. In the second example, the FSIM considers multiple items, multiple periods, multiple transportation alternatives and bundling discounts.

1.6.3 Data Collection

To validate the fuzzy integrated model (FIM), data was collected from the Turkish textile industry. As most of the textile companies are members of industry associations in Turkey, seven major industry associations were identified through an online search. Sixty-two medium-sized and large Turkish textile companies were identified as prospective organisations from which to collect data. Eight out of the sixty-two Turkish textile companies participated in the empirical validation part of this study. Two semi-structured questionnaires (to capture information on supplier performance

and feasibility) were used to collect data from twenty-four managers of these companies and this data has been analysed in the first module of the proposed model.

The results generated through the application of the FIM were compared against the actual outcomes of the SES process used by the companies (based on order quantities in 2012) to evaluate the efficacy of the FIM. Finally, the feasibility of the FIM was evaluated based on the responses received from managers of the eight companies in the two questionnaire survey.

1.7 Limitations of the Study

Even though this study has been able to deliver some significant research findings, there are several limitations that need to be acknowledged. First, disruption risks have not been considered in this study, due to technical reasons, as well as practical constraints outlined in Section 1.5. For similar reasons, the model developed in this study also does not address the full spectrum of SES issues cited in the literature.

Second, empirical validation was limited to the first module of the proposed model and data was drawn from a small sample of organisations in the Turkish textile manufacturing industry. Therefore, the generalisability of this model to other industry sectors should be approached with caution, preferably following further validation using larger samples and/or drawing on data from other industry sectors.

Third, supplier selection criteria representing environmental criteria, such as green image, pollution control and environmental management are not considered in solving the SES problem. Considerations such as the costs of carbon emissions associated with transportation alternatives have also not been included in the proposed module. However, such criteria can be included in the proposed module with minimum modifications in future studies. In a similar vein, other costs such as ordering costs,

backordering costs and warranty costs can also be added to the proposed module with relative ease, as required by the circumstances surrounding a given purchasing situation.

1.8 Thesis Outline

Chapter 2 starts with an explanation of supply chains and supply chain management. The role of outsourcing in supply chain management is discussed by providing details to emphasise the significance of supplier selection for supply chain management. Next, risk management in supply chains is explained to show the importance of supplier selection in mitigating associated risks. Different perspectives on supplier selection problems are reviewed and presented in the context of the literature to identify the gaps in current knowledge.

The details of the methodological approach followed in the development of the integrated model; that is, the way individual techniques were selected and incorporated into the two constituent modules FIM and FSIM are provided in chapter 3 and chapter 5 respectively. Similarly, detailed accounts of how the two modules were validated and verified are included in chapter 4 and chapter 5 respectively.

In Chapter 3, the FIM, involving the fuzzy analytic hierarchy process (FAHP), fuzzy complex proportional assessment of alternatives (COPRAS-F) and fuzzy linear programming (FLP) are discussed in detail. FAHP and COPRAS-F are used to analyse capability-based risks whereas FLP is used to mitigate performance-based and capability-based risks to select suppliers and to allocate orders for selected suppliers.

In Chapter 4, the FIM is validated through its application in eight textile manufacturing companies located in Turkey. The fuzzy integrated model (FIM) is applied to eight textile-manufacturing companies. The analytical results of the model are compared with the actual results from the companies. Finally, a feasibility

assessment is conducted on the sample supplier selection criteria employed, as well as on the results generated from the FIM.

In Chapter 5, the fuzzy stochastic integrated model (FSIM) is used to evaluate potential suppliers in terms of both performance-based risks and capability-based risks sequentially or concurrently. The method of using a fuzzy stochastic integrated model involving FAHP, COPRAS-F and Fuzzy Stochastic Goal Programming (FSGP) is explained in detail. FAHP and COPRAS-F are used to reduce supplier numbers to a manageable level with respect to capability-based risks. The FSGP is used to mitigate performance-based risks and to select preferred suppliers and to allocate orders. The FSIM is verified using two numerical examples. One of them considers quantity discounts for single item buying with multiple transportation alternatives in a multi-period environment. The other example incorporates bundling discounts for multiple items with multiple transportation alternatives in a multi-period environment.

Chapter 6 starts with a discussion of the merits of the two modules proposed to address the SES problem in light of the deficiencies of existing models identified through the literature review. The key findings of this study, including an evaluation of the efficacy of the proposed integrated model, are then provided along with a brief account of the key contributions of the study. Chapter 6 concludes with future research directions that can be drawn from the findings of this study.

2 LITERATURE REVIEW

2.1 Introduction

In today's competitive business environment, companies are under intense pressure to meet fast-changing customer requirements and expectations in order to sustain their competitiveness in a highly globalised market. With the increasing dependency on outsourcing, supplier selection has become one of the most critical determinants of business performance and global competitiveness for a wide range of industries (Altinoz et al., 2001; Sonmez, 2006; Aissaoui et al., 2007).

In the literature, the supplier evaluation and selection (SES) problem has been dealt with at different levels of detail from multiple perspectives. These include: from a supplier collaboration and integration perspective at the supply chain and supply network levels; from a risk mitigation perspective at the business unit and supply chain levels; and from an order allocation perspective at the product category and business unit levels. There are also further nuances such as the different purchasing contexts (new task, modified re-buy, straight re-buy, strategic re-buy) decision-making contexts (individual vs. group decision-making) and environmental contexts that need to be considered when addressing the supplier selection problem (De Boer et al., 2001; Jain et al., 2009; Ho et al., 2010; Govindan et al., 2015). The approach taken in the study reported in this thesis is focused on dealing with the SES problem from a risk mitigation perspective at the product category and business unit level. Hence, the literature review included a close examination of the factors contributing to operational risks at the business unit level, and of the alternative approaches to order allocation, including numerous techniques at the product category level. This chapter presents a summary of the literature review undertaken as part of this study.

In this study, literature were collected by using some keywords such as "supplier selection", "vendor selection", "supplier evaluation", "supply chain management" and "supply chain risks" in several academic databases, including Science Direct, Emerald, Taylor & Francis, IEEE Xplore and UOW Library. Over 400 articles and 20 books were initially scanned and then the number of these articles was narrowed down by way of answering the following questions; Is this article/book related to supplier selection?, Does this article/book consider risk or uncertainty in the supplier selection process?, Does this article/book propose any decision-making methods?, If yes, which decision-making methods were proposed in this article/book to solve the supplier selection problem?, Which supplier selection criteria were used in solving the supplier selection problem?. As a result, over 180 studies (articles and books) in total have been selected and reviewed in this study.

This chapter is organised as follows: Section 2.2 introduces the broader context of the supply chain and supply chain management in which this study is situated. Section 2.3 highlights the benefits and risks of outsourcing in the context of supply chains as identified in the literature. Section 2.4 introduces the notion of risk management, the types of risks present in supply chains and mitigation approaches used for managing supply chain risks. Section 2.5 discusses the multiple perspectives of supplier evaluation and selection. Section 2.6 provides a summary of the supplier selection criteria widely used in the literature. Section 2.7 discusses the major supplier selection models found in the literature. Section 2.8 introduces the notion of uncertainty in relation to supplier selection. Section 2.9 provides an account of the status of empirical validation of current models used in supplier selection. Section 2.10 presents a summary of research gaps identified through the literature review. The conclusion to the chapter is presented in Section 2.11.

2.2 Supply Chain Management

A typical supply chain comprises a number of entities including suppliers, manufacturing plants, warehouses and distribution centres, connected via various logistics channels, and operating to ensure the flow of products, services, finance and information between primary sources and end-users (Simchi-Levi et al., 2003; Monczka et al., 2005). Supply chain management covers the planning, coordination and facilitation of these flows across the supply chain to satisfy the requirements of end-users (Monczka et al., 2005; Ayers, 2006). The overall purpose of supply chain management is therefore to facilitate collaboration and cooperation between supply chain partners in terms of sharing information, resources and risks to optimise supply chain-wide performance by ensuring a swift and even flow of products and/or services from primary sources to end-users (Simchi-Levi et al., 2003; Lysons and Farrington, 2006). Optimising performance throughout the supply chain requires value adding activities at each stage of the chain to be undertaken in the most efficient and effective manner possible. This also implies that various decisions such as make-or-buy, sourcing and technology acquisition made by supply chain partners can have a significant impact on the performance of the supply chain.

2.3 Outsourcing in Supply Chains

Purchasing (or procurement) is one of the most important activities in supply chains. In many industry sectors, the cost of raw materials and parts can account for up to 70% of the cost of a product (Ghobadian et al., 1993). With the increasing trend of outsourcing witnessed in recent times, the contribution of purchasing decisions to organisational, as well as supply chain-level, performance is becoming ever more prominent. The literature has identified a range of benefits that can be achieved through

effective outsourcing (Simchi-Levi et al., 2003; Chopra and Meindl, 2004). These benefits include:

- Better economies of scale: Supply chain partners can exploit economies of scale through aggregation of orders in both purchasing and manufacturing.
- Mitigation of overall purchasing cost: The overall purchasing costs can be significantly reduced by using efficient purchasing transactions.
- Better forecasting and planning: Integration and coordination among buyers and suppliers can reduce component inventory levels and improve the alignment of supply and demand.
- Sharing of risks: Proper contracts enable buyers to share risks (e.g. uncertain demand) with the suppliers, and this result in higher returns for both the supplier and the buyer.
- Reduction of capital investment: Buyers can share not only the risks but also capital investment with suppliers. Even though suppliers make the investment, they in turn share this investment with their customers.
- Focusing on core competencies: By successfully choosing what value addition activities to outsource, the buyer company can focus on its core strengths, such as its specific talents, skills, and knowledge sets, to differentiate the buyer company from its competitors and these differences can help the company to take advantage of its core competencies.
- Increased flexibility: Three critical issues concerned with flexibility in industry can be dealt with by successful outsourcing, enabling the buyer company to better respond to changes in customer demand. The company can utilise technical knowledge of suppliers and improve the cycle time of product

development. The company can access new technologies and innovation through suppliers.

However, these benefits are also accompanied by certain risks as listed below:

- Loss of competitive knowledge: Sourcing various items from many different suppliers may obstruct the development of new insights, innovations and solutions within the buyer company and this can result in the loss of the company's competitive knowledge.
- Conflicting objectives: It is normal that the objectives of suppliers differ from those of buyers. For example, flexibility in outsourcing to better match supply and demand by adapting production rates as needed is an important objective for buyers. However, this objective directly conflicts with the suppliers' objective of maintaining long-term relationships based on stable commitments from buyers (Simchi-Levi et al., 2003). If demand is high, the buyer company is willing to make long-term contracts with suppliers. Otherwise, the company may prefer not to make long-term commitments or contracts (Simchi-Levi et al., 2003).
- Supply risks: If suppliers face risks, this can affect the buyer company due to late delivered items and increased purchasing costs.

Supplier selection is a central decision within the outsourcing process; it enables a company to exploit the benefits of outsourcing and to mitigate the risks of outsourcing.

2.4 Risk Management in Supply Chains

Risks are generally regarded as quantifiable effects of uncertainty and/or chance events on the outcomes or objectives of an undertaking. Risk management has been defined as a process consisting of decisions and actions concerning the acceptance of a known or measured risk and the implementation of activities to mitigate the consequences of that risk and/or the probability of its occurrence (Brindley and Ritchie,

2004). There is a wide body of literature concerning risk management. Managing risks in supply chains is one of the key approaches employed in reducing supply chain vulnerability. It is also argued that risk management can ensure long-term profitability and sustainability of supply chain operations through strengthening collaboration and coordination among supply chain partners (Tang, 2006). Supply chain risks can be broadly categorised into six major types: supply risks, process risks, demand risks, intellectual property risks, behavioural risks, and political/social risks (Tang and Tomlin, 2008). There are also alternative perspectives from which supply chain risks can be considered. For example, supply chain risks can be categorised into four types based on their sources: disruption risks (value-at-risk), environmental risks (mostly natural disasters), organisational risks (industrial action and machine breakdowns) and operational risks (miss-the-target; mostly network related uncertainties) (Jüttner et al., 2003; Kleindorfer and Saad, 2005; Tang, 2006; Yang, 2007; Bilsel and Ravindran, 2011). The probability of disruption risks occurring is relatively small, but the impacts of these risks on business operations can be severe. In comparison, the probability of operational risks is high and the impact of these risks on a business is likely to be considerably lower than that of disruption risks (Yang, 2007; Bilsel, 2009). Tang (2006) proposed four approaches for mitigating supply chain risks: supply management; demand management; product management; and information management.

As the increasing dependence on suppliers forces buyer companies to face heightened levels of supply risks, supply management should particularly focus on mitigating the impacts of such risks (Micheli et al., 2008). Tang (2006) identified five sources of operational risks in the context of order allocation, which he claimed to be a key part of supply management, as follows: uncertain demand; uncertain supply yield; uncertain capacity; uncertain lead time; and uncertain cost. Many other researchers have

identified the same or similar factors as being important determinants of operational risks in relation to supplier selection and order allocation decisions (Bilsel, 2009; Bilsel and Ravindran, 2011). As these factors are directly concerned with supplier selection decisions, and hence the objectives of this thesis, they will be treated in more detail later in this chapter.

2.5 Perspectives in Supplier Selection

There are a variety of perspectives, approaches, models, purchasing contexts and decision environments that have been considered in dealing with the SES problem in the literature. In general, the typical process of supplier selection consists of six phases, namely: (i) identification of the problem; (ii) developing the selection criteria; (iii) screening the pool of available suppliers; (iv) pre-selection of a shortlist of suppliers; (v) final selection of a set of preferred suppliers among which orders are allocated; and (vi) monitoring the performance of contracted suppliers (De Boer et al., 2001; Sonmez, 2006; Aissaoui et al., 2007). In the problem identification phase, decision-makers (DMs) of the buyer company define which organisational goals will be attained by selecting preferred suppliers. Strategic and competitive priorities concerning the operations of the buyer company are also identified in this phase and these priorities are later fed into supplier selection criteria. Even though this phase represents an important part of the supplier selection process, most of the studies reported in the literature have only considered the evaluation phase in selecting preferred suppliers (De Boer et al., 2001; Chou and Chang, 2008; Şen et al., 2008; Shen and Yu, 2009).

In the screening phase, a list of potential suppliers to source from in a given industry sector is drawn up in light of the organisational goals and competitive priorities identified in the previous phase. In general, supplier selection criteria can be divided into two categories: metrics aimed at assessing tangible supplier attributes and metrics

aimed at assessing intangible supplier attributes. The tangible attributes usually account for quantifiable, performance related aspects such as product cost, delivery lead time/reliability and defect rates. Intangible attributes are related to the capability and relationship dimensions which are difficult to measure in quantitative terms. For this reason, in the literature, criteria aimed at assessing tangible and intangible supplier attributes have widely been referred to as quantitative and qualitative criteria, respectively. Even though qualitative and quantitative criteria are aimed at assessing complementary attributes of supplier performance and capabilities, most of the studies on SES have considered either qualitative or quantitative criteria, but not both (Kahraman et al., 2003; Kilincci and Onal, 2011; Arikan, 2013). In pre-selection, the aim is to reduce the potentially large pool of suppliers available in the market to a smaller set of acceptable suppliers. As such, this phase is concerned with sorting rather than ranking (De Boer et al., 2001). In the final evaluation phase of the process, shortlisted suppliers are ranked based on a thorough and detailed evaluation of all relevant attributes using the criteria developed in phase 2, before allocating orders among the preferred suppliers. The vast majority of the studies reported in the supplier selection literature have extensively dealt with the final selection, which is the fifth phase in the process, and it involves selecting the best suppliers and allocating orders among them. Lastly, the performance of selected suppliers against the predefined criteria (developed in phase 2) is undertaken as per the terms of the contract in the monitoring phase.

The purchasing contexts considered in supplier selection are: new task, straight re-buy (commodity or routine items), modified re-buy (collaborative or leverage) and strategic re-buy (bottleneck or custom), which recognise different levels of significance and complexity associated with the purchasing situation (Faris et al., 1967; Kraljic,

1983; De Boer et al., 2001; Leenders, 2006; Gordon, 2008). A new task is the most complex context, partly due to the high level of uncertainty and lack of adequate information regarding potential suppliers (De Boer et al., 2001). In straight re-buy situations, less experienced middle managers manage a small set of suppliers to consolidate volume, obtain the lowest price, optimise inventory level and concentrate on operational efficiency (Kraljic, 1983; De Boer et al., 2001; Leenders, 2006; Gordon, 2008). Modified re-buy and straight re-buy situations are quite similar in terms of the dependency level on suppliers; however, purchasing cost in a modified re-buy situation is higher than in straight re-buy. Thus, in modified re-buy, more senior managers are involved in managing a smaller number of suppliers. These suppliers are selected from an approved shortlist, and are given short-term contracts, to achieve cost reductions, encourage collaboration and aggregate and optimise volumes (Kraljic, 1983; De Boer et al., 2001; Gordon, 2008). De Boer et al. (2001) proposed a strategic re-buy approach to managing suppliers of bottleneck and strategic items. For bottleneck items, department heads are involved in managing relationships with a few suppliers (difficult to switch) in long-term contracts to ensure the availability of suppliers, and to develop relationships, ensure volumes, and improve reliability or predictability (Kraljic, 1983; De Boer et al., 2001; Leenders, 2006; Gordon, 2008). Managing suppliers for purchasing strategic items is more complex than managing for bottleneck items. For example, top-level managers are required to manage and control a smaller number of suppliers (difficult to switch and adequate technical capability) in medium- or long-term contracts to promote supplier collaboration, analyse risk, concentrate availability, quality and reliability of suppliers, develop partnerships, save costs and implement improvements (Kraljic, 1983; De Boer et al., 2001; Leenders, 2006; Gordon, 2008).

The level of buyer-supplier relationship has also been cited as an important aspect of supplier selection in literature (Ghodsypour and O'Brien, 1998; Chan, 2003; Şen et al., 2008). The relationships can be categorised into five types (Chan, 2003). In level 1, there is no integration or very low integration between supplier and buyer in purchasing non-critical items, and cost and quality are the most important criteria in selecting suppliers (Ghodsypour and O'Brien, 1998; Chan, 2003; Şen et al., 2008). Relationships at this level can be called temporarily basic relationships or traditional relationships (Faris et al., 1967; Chan, 2003; Perona and Saccani, 2004). With the increasing degree of integration level, the number of criteria involved in supplier selection is progressively increased and the relationships with suppliers become progressively stronger at each level (Chan, 2003; Şen et al., 2008). For example, reliability, flexibility, supply lots and lead-time are taken into account in addition to cost and quality in selecting suppliers at level 2 and relationships at this level are called temporarily operational relationships (Ghodsypour and O'Brien, 1998; Chan, 2003). At level 3, elements of the process capability of suppliers, including set-up time, lot size, and lead time, besides the criteria used at previous levels are considered in selecting suppliers. Relationships at this level are called cyclically operational relationships and they are similar to straight re-buy situations (Faris et al., 1967; Chan, 2003; Perona and Saccani, 2004). At level 4, criteria capturing the human resources aspects of suppliers, besides the criteria used in previous levels, are considered to control product and production processes when selecting and evaluating suppliers. Relationships at this level are called long-lasting tactical relationships (Ghodsypour and O'Brien, 1998; Chan, 2003; Şen et al., 2008). Level 5, is the top level for integration or cooperation between suppliers and buyers. Relationships at this level are called long-lasting strategic relationships (Chan, 2003; Şen et al., 2008). Technological capability and degree of

closeness between supplier and buyer, besides the criteria used in previous levels, are taken into account in evaluating suppliers at this level (Chan, 2003).

Further to the perspectives discussed above, there are other nuances of the supplier selection problem that have been reported in the literature. These situational variances include: the number of suppliers to be contracted (single vs. multiple suppliers), the number of purchasing objectives to be considered (single vs. multiple objectives), the number of decision-makers involved (individual vs. group decision-making), the number of products being considered (single vs. multiple items), the number of inventory periods/cycles to be accounted for (single vs. multiple periods), and the decision environments applicable (deterministic vs. stochastic) (Ghodsypour and O'Brien, 1998; Aissaoui et al., 2007; Chai et al., 2013).

If a selected supplier has the production capacity to fulfil the complete order requirements of the buyer, the purchasing situation is called single-sourcing. In this situation, the buyer will try to answer the question "which supplier is the best?" in a qualified pool of suppliers. However, if the production capacity of a supplier is not sufficient to fulfil the full order requirements of the buyer, the buyer should work with more than one supplier. This situation is called multiple sourcing. In this situation, the buyer should answer a two-part question: "Which suppliers are the best, and how much should be purchased from each of the preferred suppliers?" (Ghodsypour and O'Brien, 1998). Some authors have proposed models to solve the SES problem which incorporate only one objective; generally the cost. These models express all supplier attributes or selection criteria in dollar terms. The other models presented in the literature, in general, treat the supplier selection problem as a multi-objective or multi-criteria decision problem (Ghodsypour and O'Brien, 1998).

Individual and group decision-making situations are also considered as nuances of the SES problem. Additionally, the performance of suppliers is evaluated for single items or multiple items, and this evaluation process may consider a single period or multiple periods. In the next section, the literature specifically related to supplier selection criteria will be presented and evaluated.

2.6 Supplier Selection Criteria

The criteria used in the evaluation and selection of suppliers in the literature are wide and varied, and still evolving. Most of the traditional approaches in the literature considered price as the sole criterion for many years after the notion of purchasing was first introduced in the 1960s (Degraeve and Roodhooft, 1999). Although price remains a key metric in the criteria used in current supplier selection models, a large number of other metrics have been added over the years to account for both performance-related and capability-related attributes of suppliers. As outlined in the previous section, supplier selection criteria can be broadly divided into qualitative and quantitative criteria (Ghodsypour and O'Brien, 1998; Monczka et al., 2005; Ha and Krishnan, 2008). Consideration of qualitative and quantitative metrics together, in a single model, enables treatment of both tangible and intangible supplier attributes while considering their complementary contributions to solving the supplier selection problem more comprehensively. However, this has only been recognised in more recent studies reported in the literature.

Monczka et al. (2005) introduced three important quantitative criteria in their model, which are: delivery performance, quality performance and cost performance. Many subsequent studies in the literature have included these three quantitative performance-based criteria as objectives in their supplier selection models (Amid et al., 2006; Kumar et al., 2006; Amid et al., 2011). Other researchers have recognised the

variability associated with these three criteria and have viewed them in terms of operational risks (Tang, 2006; Bilsel and Ravindran, 2011). Mitigating the impact of these operational risks has also been attempted through the use of stochastic methods. However, a key limitation of these stochastic models is that they only consider quantitative criteria used in the supplier selection process. Therefore, there is a need for incorporating suitable methods into future models to account for the uncertainty or variations associated with intangible supplier attributes that are usually captured with the use of qualitative criteria.

2.7 Supplier Selection Methods

In recognition of the increasing range of tangible and intangible supplier attributes that need to be considered, and the diverse nature of purchasing contexts in which they are applied, over the years, researchers have developed a multitude of models to aid SES decisions. These models have incorporated hundreds of evaluation methods and ranking techniques. Additionally, in recent times, these methods have been combined into hybrid or integrated models in order to compensate for certain limitations of the individual methods. This section provides a summary account of the five major categories of individual methods found in the extant literature, as well as the integrated or hybrid models that have been proposed over the past several years:

- linear weighting techniques
- mathematical programming models
- total cost of ownership models
- artificial intelligence models
- statistical models
- integrated or hybrid models.

2.7.1 Linear Weighting Techniques

Linear weighting techniques are the simplest methods that can be used to both sort or rank suppliers. In the most basic linear weighting technique, weights reflective of their relative importance are first assigned to the evaluation criteria used, considering the strategic and operational priorities of the buyer organisation. This is followed by the assignment of ratings indicative of supplier capability and performance under each criterion, usually based on expert judgment or the past experience of decision-makers. These ratings are then multiplied by the weights assigned to each criterion to arrive at a weighted rating for each supplier under each criterion. These weighted ratings are then aggregated by following either a compensatory or non-compensatory rule into a single weighted score for each supplier. Apart from their obvious simplicity, these weighting models have the advantage of being capable of accommodating both tangible and intangible attributes and handling imprecise data. However, they suffer from lack of objectivity and capacity to allocate order quantities. The more advanced (improved) versions of linear weighting techniques that have been proposed in the literature include: multi-attribute utility methods, outranking methods, compromise methods and fuzzy set theory (FST) (De Boer et al., 2001; Chai et al., 2013). In multi-attribute utility methods, a utility value is given for each supplier in order to rank them for the selection process. Multi-attribute methods may also employ an analytic hierarchy process (AHP) and analytic network process (ANP) for pair-wise comparison of criteria (Saaty, 1990; Saaty, 2004). Several outranking methods, including the elimination and choice expressing the reality (ELECTRE) and preference ranking organisation method for enrichment evaluations (PROMETHEE), have also been proposed in the literature. ELECTRE, which can be considered as quasi-compensatory, uses the analysis of outranking relations among the suppliers through concordance and discordance indices

to evaluate the performance of suppliers (De Boer et al., 2001; Sevkli, 2010). PROMETHEE utilises pair-wise comparison of suppliers and grades the suppliers in the 0–1 interval (Chen et al., 2011; Chai et al., 2013). Compromise methods, which are the technique for order preference by similarity to ideal solution (TOPSIS) and the multi-criteria optimisation and compromise solution (VIKOR), attempt to obtain a solution which is as close as possible to the ideal solution (Chai et al., 2013). TOPSIS, which is simple to implement, uses vector normalisation (Opricovic and Tzeng, 2004; Sanayei et al., 2010). VIKOR, on the other hand, uses linear normalisation (Opricovic and Tzeng, 2004; Sanayei et al., 2010). FST is a useful method to handle uncertainty in supplier selection problems (De Boer et al., 2001). FST has been combined with different linear weighting techniques, and mathematical programming models to handle uncertain qualitative or quantitative data more efficiently in the supplier selection process. Other methods in the linear weighting family are the simple multi-attribute rating technique (SMART) and the decision-making trial and evaluation laboratory (DEMATEL). SMART, which can consider and analyse qualitative and quantitative criteria, uses a simple additive weighting method to obtain a total performance value for each supplier (Chou and Chang, 2008; Chai et al., 2013). DEMATEL uses digraph separation into cause and effect groups to analyse causal relations among complex criteria (Chang et al., 2011; Büyüközkan and Çifçi, 2012; Chai et al., 2013). As most of these linear weighting techniques (except FST) are ineffective in handling uncertainty, they have been combined with FST or grey relational analysis (GRA) to improve their ability to handle uncertainty (Chou and Chang, 2008; Büyüközkan and Çifçi, 2012; Chai et al., 2013).

2.7.2 Mathematical Programming Methods

Mathematical Programming Methods (MPMs) can be employed to evaluate suppliers more accurately and objectively in situations where historical performance data or numerical data pertaining to other supplier attributes (e.g. capacity) are readily available (De Boer et al., 2001). As these methods rely on objective (quantitative) data, they are not suitable for handling qualitative data such as decision-makers' judgements regarding supplier capability or capacity to assimilate new technology. The family of MPMs include linear programming (LP), integer linear programming (ILP), mixed-integer linear programming (MILP), nonlinear programming (NP), mixed integer nonlinear programming (MINLP), goal programming (GP), data envelopment analysis (DEA) and multi-objective programming (MOP) (De Boer et al., 2001; Ho et al., 2010; Chai et al., 2013). Even though MPMs can provide optimum solutions and objective assessments, they cannot consider the subjective opinions of decision-makers (Ghodsypour and O'Brien, 1998; Jain et al., 2009).

2.7.3 Total Cost of Ownership

Total Cost of Ownership (TCO) models consider all costs associated with the acquisition and subsequent use of a purchased item, including those related to quality, delivery, service, maintenance and disposal, incurred over the entire life of that item (Ramanathan, 2007; Dogan and Aydin, 2011). Although this approach is popular within the area of management accounting, the difficulties associated with quantifying all costs can be a significant barrier to its use. This could be particularly problematic when dealing with a variety of items with low unit costs as opposed to a smaller number of capital intensive items. Additionally, establishing the costs associated with factors such as service and on-time delivery can also be particularly challenging – other techniques such as rating systems have been combined with TCO to overcome this problem.

2.7.4 Artificial Intelligence Models

Artificial Intelligence Models (AIMs) which are generally implemented with the aid of computer systems can be divided into two groups: major AIMs including genetic algorithms (GAs), neural networks (NN), particle swarm optimisations (PSOs), ant colony algorithm (ACA), and expert systems (ESs), as well as other minor AIMs such as case-based reasoning (CBR), fuzzy set theory (FST), Bayesian networks (BN), grey system theory (GST), rough set theory (RST), Dempster-Shafer theory (DST), association rule (AR), support vector machine (SVM) and decision tree (DT) (De Boer et al., 2001; Chai et al., 2013). These models often require additional expertise to model and solve supplier selection problems using computational algorithms. These techniques can formulate and solve new problems based on previous scenarios or expert knowledge. As such, they are considered to be capable of dealing more effectively with the complexity and ambiguity associated with the SES problem. However, given the abstract nature of the computer-based algorithms employed, interpretation of the decision logic followed with artificial intelligence (AI) techniques can be problematic. In other words; AI approaches tend to use black box type input-output models, and the underlying computational techniques or algorithms employed in such models are hard for decision-makers to understand. Furthermore, AI methods require setting up a range of algorithmic parameters, which further restricts their use in practice.

2.7.5 Statistical Models

Statistical models, by comparison, are particularly suitable for dealing with uncertainty surrounding the SES problem such as random variations in demand or lead time. Principal component analysis (PCA), factor analysis (FA) and structural equation modelling (SEM) are some of the statistical models that have been cited in the literature (Petroni and Braglia, 2000; Kannan and Tan, 2002; Punniyamoorthy et al., 2011). These

techniques can consider both qualitative and quantitative data for solving the SES problem. Although they are suitable for solving the SES problem more comprehensively at an aggregate level, some inherent limitations can act as impediments to generating accurate and tangible solutions. For example, the reliability of the results is directly associated with the size of data samples used. Lack of historical data may also act as a barrier to the effective application of these models.

2.7.6 Integrated Models

In recent times, there has been a sharp increase in the combined or integrated methods proposed in the literature to solve the SES problem. The integrated models leverage the complementary strengths of individual methods or techniques in order to address the multiple facets of the SES problem better while accounting for differences in situational factors at the same time (Chan et al., 2008; Amid et al., 2009; Tsai and Hung, 2009; Sevkli, 2010; Amid et al., 2011; Lin, 2012).These integrated methods can be classified into five major groups:

- Integrated Multi-attribute Utility Models
- Integrated Outranking Models
- Integrated Compromise Models
- Integrated DEA Models
- Integrated Artificial Intelligent Models.

2.7.6.1 Integrated multi-attribute utility models

Of the multi-attribute utility models, AHP is the most widely used method to deal with the ambiguity present in decision-makers' judgements when solving multi-criteria problems. However, in most of the recent models AHP has been used in combination with fuzzy logic (Fuzzy AHP) to solve the SES problem in a way, which addresses uncertainty more efficiently than with AHP. For example, Kahraman et al.

(2003) and Kilincci and Onal (2011) both applied fuzzy AHP (FAHP) to deal with the uncertainty in the SES problem for Turkish white goods manufacturer. Other researchers have used FAHP to solve the SES problem with a particular focus on addressing global risks and inbound supply risks (Chan and Kumar, 2007; Chan et al., 2008; Ganguly and Guin, 2013). Furthermore, researchers have used different approaches when combining fuzzy logic and AHP in order to address the issues of inconsistency and/or uncertainty of human preference. For example, some authors have proposed the integration of fuzzy preference relations and AHP (Chamodrakas et al., 2010; Chen and Chao, 2012), whereas others have suggested an integrated model consisting of basic fuzzy logic and AHP (Labib, 2011). Overall, compared to AHP, which utilises crisp numbers to capture decision-makers' judgements, FAHP has the advantage of accounting for the vagueness surrounding decision-makers' judgements with the use of fuzzy numbers, which provides a better reflection of real world settings.

The use of FAHP alone is not sufficient to address the full range of challenges associated with the SES problem. For example, FAHP is not sufficient to handle quantitative data. Therefore, FAHP has been combined with other methods. FAHP and statistical methods (cluster analysis and structural equation modelling) have been integrated to reduce the number of potential suppliers progressively (e.g. using cluster analysis) and to test and estimate the relationships between the criteria used and the chances of selecting suitable suppliers (e.g. structural equation modelling). Bottani and Rizzi (2008) integrated FAHP and cluster analysis to select the most preferred cluster in which the best suppliers were, considering customer satisfaction, supplier's willingness, technical and organizational capabilities and the firm's interests. Punniyamoorthy et al. (2011) integrated FAHP and structural equation modelling (SEM) to test and estimate the relationship between criteria used in solving the SES problem and the chances of

selecting preferred suppliers utilising data collected in a sample of 151 respondents in the Indian boiler manufacturing industry. Additionally, FAHP has been integrated with interpretive structural modelling (ISM) to determine relationships among criteria and with benefits, opportunities, cost and risks (BOCR) analysis to identify supplier selection criteria with respect to company strategies, and to separate criteria in four clusters namely, benefits, opportunities, cost and risks. Yang et al. (2008) proposed a hybrid model to clarify the interrelationships among the sub-criteria used, combining four individual techniques to solve the SES problem for a Taiwanese electronic component manufacturer. The four techniques used were: triangular fuzzy numbers for expressing preferences of decision-makers in relation to supplier selection criteria; ISM for identifying interrelationships among sub-criteria (developing the selection criteria phase of supplier selection phase (DSCP)); FAHP for calculating the weights of each criterion, and non-additive fuzzy integral methods for computing fuzzy synthetic performance of criteria (final selection phase of supplier selection (FSP)). Lee (2009a) and Lee (2009b) combined FAHP and BOCR to deal with the SES problem in uncertain environments by way of considering buyer-supplier relationships between a manufacturer and its suppliers with respect to benefits, opportunities, cost and risks. FAHP has also been combined with artificial intelligence techniques. Şen et al. (2010) proposed a hybrid model to determine supplier selection criteria based on the level of buyer-supplier relationship in solving the SES problem for a Turkish electronic company. This model combines three individual techniques: a framework to determine supplier selection criteria (DSCP) influencing the purchasing decisions of a company according to the level of buyer-supplier relationship, an FAHP to determine the weights of supplier selection criteria and a max-min heuristic approach to evaluate the performance of suppliers against these weighted criteria (FSP).

Even though these models have proved to be useful in solving supplier selection problems more comprehensively, they generally do not consider supplier performance, particularly in terms of beneficial and non-beneficial criteria. To fill this gap, some researchers have included the technique for order preference by similarity to an ideal solution (TOPSIS). Wang et al. (2009) proposed fuzzy hierarchical TOPSIS, which has been used to provide more objective criteria weights compared to traditional TOPSIS, in selecting preferred suppliers incorporating the simplified parameterised metric distance method and FAHP. Zeydan et al. (2011) combined FAHP, fuzzy TOPSIS (FTOPSIS) and DEA to evaluate the performance of suppliers using both qualitative and quantitative data.

Some authors have attempted to combine non-fuzzy AHP with a number of other methods for the purpose of considering different types of data, such as grey data in addressing uncertainty. For instance, AHP has been combined with other methods instead of the fuzzy concept to analyse the variability associated with decision-makers' preferences in the SES process. Grey relational analysis (GRA) and AHP were integrated to obtain satisfactory outcomes using a small amount of input data in solving the SES problem (Yang and Chen, 2006; Pitchipoo et al., 2012). In both of the studies mentioned above, AHP was used to calculate the weights of qualitative criteria used and GRA was utilised to evaluate the performance of suppliers with respect to both qualitative and quantitative criteria. Another method used in combination with AHP to account for uncertainty in the supplier selection process is Dempster-Shafer Theory (DST). For instance, Deng et al. (2014) integrated AHP with D numbers generated using DST to extend a fuzzy preference relation to be used with AHP to solve the SES problem more efficiently in uncertain environments, whereas Ganguly (2014) integrated AHP and DST to mitigate supply risks in the evaluation of supplier performance. Other

studies have proposed the integration of AHP and DEA to measure the efficiency of suppliers in terms of qualitative data (or scores) and quantitative data. For example, Ramanathan (2007) proposed an integrated model involving total cost of ownership (TCO) to compute quantitative data (cost-related), AHP to compute qualitative data, and DEA to evaluate the performance of suppliers using these qualitative and quantitative data. Additionally, Sevkli et al. (2007) applied a combination of DEA and AHP, which they called data envelopment analytical hierarchy process (DEAHP), to improve the performance of AHP with regard to outcomes such as performance scores in solving the SES problem for a Turkish TV set manufacturer. Ha and Krishnan (2008) also proposed an approach combining AHP, DEA and neural networks (NN) which considers qualitative and quantitative criteria to draw an efficient supplier map to select preferred suppliers within different segments for an automobile company. This model enables a buyer company to select single or multiple suppliers based on combined scores. In the above study, AHP was used to assign weights for qualitative criteria. Then, both these weights and quantitative data were evaluated in DEA and NN to select the best suppliers. Even though these approaches are sufficient for measuring the performances of suppliers, they do not consider the requirements of buyer companies such as compliance with social and environmental obligations and reliability of order fulfilment. Therefore, some studies have proposed quality function deployment (QFD) to incorporate the requirements of buyer companies into supplier selection models. Ho et al. (2011) integrated QFD and AHP to identify the requirements of company stakeholders and used these in evaluating the performance of suppliers for an automobile manufacturing company. In the above study, the requirements of company stakeholders were converted into supplier selection criteria (DSCP) by using QFD, and the importance of each of these criteria and the performance of suppliers were

determined by using AHP. Rajesh and Malliga (2013) also integrated QFD and AHP to consider the impact of company strategies and the requirements of company stakeholders in solving the SES problem. In their model, QFD was used to assign weights to criteria. The weights were then used as coefficients in AHP to select preferred suppliers. Although these studies are useful for supplier selection, they do not consider order allocation.

Other studies have proposed integrated models combining AHP and GP (or multi-objective programming) to solve supplier selection problems and to allocate orders among preferred suppliers. For example, Çebi and Bayraktar (2003) proposed an integrated model involving AHP and lexicographic GP, whereas Perçin (2006) proposed a model including AHP and pre-emptive GP to select the best suppliers and allocate order quantities for these suppliers. In these studies, AHP was used to obtain a utility value for each supplier based on qualitative criteria. Then, these utility values were placed into total utility objective function as coefficients in GP. The total utility objective function and three objective functions (quality, delivery, and cost) were then maximised (utility objective function and quality) and minimised (delivery and cost) together (Çebi and Bayraktar, 2003). Perçin (2006) added an extra objective function (service) to these four objective functions (utility objective function, quality, delivery and cost). Therefore, these studies consider qualitative and quantitative data together. Xia and Wu (2007) proposed an integrated model which included AHP scores for each supplier to use as coefficients in the total score objective function, and multi-objective programming which considered objective functions (maximisation of total score, on time delivery, minimisation of cumulative price breaks, number of defective items) with volume discounts to help allocate orders. Mendoza et al. (2008) integrated three techniques: L_p metric, to screen an initial list of suppliers and to reduce the number of

suppliers to a manageable shortlist, AHP to derive a score for each supplier to use as a coefficient in the total score goal and pre-emptive GP when considering goals (total score, distance, process capability, flexibility, quality, service level, purchasing expenses and lead-time) to allocate orders for selected suppliers. Amin and Zhang (2012) developed an integrated model consisting of two phases to solve the SES problem for a closed loop supply chain. In the first phase of the this model, a comprehensive framework covering both qualitative and quantitative criteria was suggested to enable decision-makers to assign weights to criteria. Then, the performances of suppliers were evaluated by using the fuzzy concept against the set criteria. In the second phase, multi-objective MILP, which was used to determine preferred suppliers and refurbishing sites to allocate orders in reverse logistic, was solved by assigning weights to each objective function by using FAHP and compromise programming (FSP). Omid et al. (2008) proposed a hybrid model incorporating AHP, TOPSIS and multi-objective MILP to solve a special discount where quantity and bundling discounts were combined. AHP and TOPSIS were used to evaluate the performances of suppliers with respect to qualitative criteria to obtain scores for each supplier. These scores were then transferred into multi-objective MILP to allocate order. In another study, Wu et al. (2009) proposed an integrated model combining ANP (instead of AHP) and MILP to consider bundling discounts in a SES problem. In this study, ANP was used to evaluate suppliers with respect to qualitative criteria and to obtain a score for each supplier. These scores were then used as coefficients of performance constraints in MILP to allocate orders. These papers propose efficient ways of solving the bundling discount problem, however, they have not accounted for the variability associated with quantitative data.

Some studies suggest using integrated models of ANP to treat the dependence (inner and outer dependence) between the criteria used, and to provide feedback between criteria in different levels of hierarchy in solving the SES problem. Demirtas and Ustun (2008), Ustun and Demirtas (2008) and Demirtas and Ustun (2009) used integrated ANP and multi-objective MILP (or GP) to analyse dependence between supplier selection criteria in selecting preferred suppliers and in allocating order quantities for these suppliers. In the above studies, ANP was used to assign weights to criteria, which were based on BOCR. These weights were then placed into one of the three objective functions as coefficients in the multi-objective MILP (or GP) model. Tseng et al. (2009) proposed an integrated model which includes ANP to analyse supplier selection criteria and the Choquet integral to eliminate the need for subjective judgements by decision-makers, and to capture interdependencies of criteria in solving the SES problem for a Taiwanese electronics company. Razmi and Rafiei (2010) combined ANP and mixed-integer nonlinear programming to solve the SES problem for strategic items. In their paper, ANP was used to qualify suppliers according to their qualitative attributes so as to make a shortlist of suppliers. Mixed-integer nonlinear programming considering inventory and supplier switching costs were then used to select the preferred suppliers and to allocate orders among them. Lin et al. (2010) proposed a combined model which was used to efficiently analyse interrelationships amongst criteria. The model used ISM to determine the relationships and interrelationships amongst criteria and ANP to arrange weights for these criteria, and to rank suppliers against these criteria to solve a SES problem for a semiconductor company. Lin et al. (2011) integrated TOPSIS, ANP and LP to select preferred suppliers, using ANP and TOPSIS to evaluate the performance of suppliers to obtain total purchase value considered in LP as a single objective, and LP was used to select

preferred suppliers and to allocate orders to save costs, in acquiring enterprise resource planning systems by Taiwanese motherboard manufacturer.

ANP is not capable of handling uncertain and ambiguous data well, so some papers in the literature have combined the fuzzy concept with ANP and other techniques. Önüt et al. (2009) proposed an integrated model combining fuzzy ANP (FANP) and fuzzy TOPSIS (FTOPSIS) to consider beneficial and non-beneficial criteria to solve a SES problem for a telecommunications company. In this study, FANP was used to assign weights to supplier selection criteria. These weights were then inserted into FTOPSIS to evaluate the performance of suppliers. Yücenur et al. (2011) used FAHP and FANP individually to solve a SES problem in a global procurement context, and then compared the results. Büyüközkan and Çifçi (2012) integrated fuzzy DEMATEL, FANP and FTOPSIS to identify cause-effect type relationships in selecting suitable green suppliers for a motor company. In this study, fuzzy DEMATEL and FANP were used to determine the weights of the criteria used, and FTOPSIS was used to rank suppliers according to their performance against these criteria and the weights of the criteria. Even though these studies are effective in handling uncertainty in data used in the supplier selection process, they do not consider variability in important quantitative data (e.g. the demand for the items concerned and the production capacity of suppliers).

2.7.6.2 Integrated outranking models

Outranking methods such as ELECTRE and PROMETHEE, have been combined with entropy weight or fuzzy logic methods to obtain weights for criteria or to handle uncertainty pertaining to the SES problem. For example, Montazer et al. (2009) proposed a fuzzy expert system consisting of evaluating modules (fuzzy rule base) to obtain scores for suppliers and a ranking module (fuzzy ELECTRE III) to rank

suppliers to provide an operationally effective expert system to be used by decision-makers when solving the SES problem in uncertain environments. Sevkli (2010) also applied and compared the results of crisp and fuzzy ELECTRE for supplier selection for a propeller shaft manufacturing company. Chen et al. (2011) applied fuzzy PROMETHEE for information system/information technology sourcing for a Taiwanese bank. Liu and Zhang (2011) used an integrated model to obtain objective weights for the criteria used, including the entropy model, and each index (threshold, harmoniousness and inharmoniousness index) and ELECTRE III to rank suppliers against criteria. Although these models are effective for analysing variability associated with qualitative data, they do not consider variability in quantitative data or allocate orders among preferred suppliers.

2.7.6.3 Integrated compromise models

TOPSIS and VIKOR, which are considered compromise methods, have been combined with fuzzy logic to evaluate supplier performance. For example, Chen and Wang (2009) applied fuzzy VIKOR for information system/information technology sourcing for a Taiwan-based computer manufacturer. Sanayei et al. (2010) proposed extended fuzzy VIKOR to consider both qualitative and quantitative criteria to provide a systematic and flexible solution to enable decision-makers to identify the outranking order of suppliers, and to evaluate and rate suppliers to solve a SES problem. Shemshadi et al. (2011) used a Shannon entropy model to obtain objective weights for supplier selection criteria and fuzzy VIKOR to rank suppliers in solving a SES problem as a group multi criteria decision-making model (MCDM). Shen et al. (2013) suggested using FTOPSIS to evaluate the performance of suppliers in solving the green SES problem for an automobile company. Roshandel et al. (2013) also developed a hierarchical FTOPSIS to select preferred suppliers for an Iranian health products

producer. In another study, Kannan et al. (2014) proposed FTOPSIS to select preferred suppliers for a Brazilian electronics company in the context of green supply chain management. Additionally, a number of authors have compared and proposed FTOPSIS with geometric mean-based FTOPSIS and graded mean integration FTOPSIS by using Spearman's rank correlation coefficient. A limited number of these studies have considered order allocation using LP, multi-choice goal programming (MCGP) and MILP. For example, Guneri et al. (2009) integrated the FTOPSIS concept and LP considering both qualitative and quantitative data for supplier selection. In the above study, a fuzzy concept was used to assign weights to the criteria used and to obtain scores for each supplier. These scores were then inserted into an LP model containing a maximisation objective function to select suppliers and allocate orders among those suppliers. Liao and Kao (2011) proposed an integrated model to enable decision-makers to set multiple aspiration levels in the context of multi-choice goal programming. Their model includes FTOPSIS and MCGP to solve a SES problem for a watch manufacturing company. In this study, FTOPSIS was utilised to assign a score to each supplier with respect to the qualitative criteria used. These scores were then transferred into MCGP as coefficients for one of the four goals in allocating order quantities. Singh (2014) integrated strengths, weaknesses, opportunities, threats (SWOT), FTOPSIS and MILP considering both qualitative and quantitative data to solve a SES problem systematically. SWOT was used to determine candidate suppliers and selection criteria with respect to the strengths of the company and opportunities present in the market. Then, FTOPSIS was used to evaluate the performance of suppliers as per the selection criteria used. After this, the outputs of FTOPSIS were inserted into MILP as coefficients of the total purchase value. Then, MILP was used to maximise the total purchase value,

while satisfying the requirements of demand, budget and average delivery time, as well as suppliers' capacity constraints.

2.7.6.4 Integrated DEA models

DEA, which is a mathematical model, allows the inclusion of multiple inputs and outputs to determine non-dominated solutions and to measure the relative efficiency of suppliers in the supplier selection process (Wu and Olson, 2008a; Wu and Blackhurst, 2009). DEA has also been combined with different methods/approaches (e.g. stochastic DEA, fuzzy DEA and augmented DEA) to evaluate the performance of suppliers more efficiently and to select preferred suppliers in uncertain environments. For example, Wu and Olson (2008a) compared stochastic dominance with stochastic DEA considering stochastic quantitative data in solving a SES problem. Additionally, Çelebi and Bayraktar (2008) proposed an integrated model which they used to overcome the issue of incomplete information in relation to the criteria used to solve a SES problem for an automobile company. NN was used to reduce the set of attributes and to determine the weights of criteria, and DEA was used in the final evaluation of the performance of suppliers. Wu and Olson (2008b) compared the simulation results of three methods, namely chance-constrained programming (CCP), DEA and MOP in solving a SES problem. Wu and Blackhurst (2009) proposed an augmented DEA, which offered improved discriminatory power compared to traditional DEA models for ranking suppliers for a global company providing communication and aviation electronics. Wu (2010) proposed stochastic DEA to consider risks, uncertainty and other intangible criteria in solving a global SES problem. Toloo and Nalchigar (2011) proposed a modified DEA, taking into account both cardinal and ordinal data. Azadeh and Alem (2010) proposed three different models: DEA, fuzzy DEA and chance constraint DEA (CCDEA) and compared the results of these models for choosing the

most appropriate model for solving a SES problem. Chen (2011) proposed an integrated model, which was used to provide a systematic solution for a SES problem. This model combined four techniques: SWOT, DEA, TOPSIS and DELPHI. In this study, SWOT was used to identify company strategies and DEA was used to screen the performance of suppliers. In the final stage, TOPSIS was used to rank suppliers and DELPHI was used to monitor supplier performance. Songhori et al. (2011) combined DEA and MILP when considering transportation alternatives in a SES problem for an automobile company. The above model consists of two phases; determining the efficiency of suppliers by DEA and an allocation phase using MILP. Songhori et al. (2011) were the first to consider transportation alternatives, and did not consider qualitative data and variability associated with quantitative data. In another attempt to solve a transportation alternatives problem, Arabzad et al. (2015) developed a mathematical model that consists of a robust multi-objective MILP and LP-metric method in the facility location-allocation problem to plan a supply chain. Two objective functions were formulated by using a multi-objective MILP, and they were combined using an LP-metric method to be solved as a single objective MILP. The uncertainty in customers' demand and cost indicators were handled by a scenario-based approach. Even though these studies were efficient at solving transportation the SES problem, they do not consider qualitative data and the variability associated with quantity data together.

2.7.6.5 Integrated artificial intelligent models

Artificial Intelligent Models (AIMs) have been combined with other models to address numerous complications in the SES problem. Some AIMs (GST, RST, DST, FST, BN) have been used to handle large amounts of quantitative and qualitative data efficiently while dealing with vagueness and uncertainty associated with the pre-selection or evaluation phase of the SES process. Researchers have sometimes

combined these models with other models in an effort to provide a more robust solution to the SES problem. For example, Li et al. (2008) proposed an integrated model including GST and RST, which was called to grey-based rough set, to efficiently address the SES problem in uncertain environments, whereas Wu (2009a) used GRA to reflect uncertainty in the criteria used, and DST to aggregate the preferences of decision-makers in evaluating the performances of suppliers. Bai and Sarkis (2010) expanded the grey-based rough set, which was introduced by Li et al. (2008), with additional layers, in order to consider sustainability criteria. Fuzzy set theory has also been combined with other AIMs. For example, Tseng (2011) used the fuzzy concept to assign weights to the criteria used, and grey degrees to rank suppliers using incomplete information for solving green SES problem for a Taiwanese electronic company. Fuzzy set theory has also been combined with other approaches, such as QFD and c-means. For example, Dursun and Karsak (2013) developed a QFD-based fuzzy MCDM approach to consider relationships between product features and supplier selection criteria and to enable a group of decision-makers to identify similarities and differences between their opinions in solving the SES problem. In the above study, QFD was used to evaluate the performances of suppliers by using two interrelated Houses of Quality matrices and the fuzzy weighted average method was used to determine the upper and lower bounds of weights pertaining to the selection criteria used and the ratings of suppliers. Omurca (2013) used fuzzy c-means to cluster suppliers and RST to determine core selection criteria and extract the decision rules to determine the specific characteristics of clusters. It has been claimed that the above model could handle the imprecision of human judgements robustly. Additionally, Bayesian Networks (BN) have been used to handle imprecise data in selecting suppliers. For example, Dogan and Aydin (2011) proposed an integrated model, which they used in order to overcome the

dilemmas of buyers, including limited and uncertain information regarding suppliers. They used the TCO concept to provide final total cost attributes and Bayesian Networks (BN) to model the relationships between supplier selection criteria and cost attributes in solving a SES problem for an automobile company. Several other AIMs (GA, Tabu Search (TS)) have also been used to solve the SES problem. For example, Yeh and Chuang (2011) proposed an MOP using four objective functions, which were minimisation of total cost, minimisation of total time, maximisation of average product quality and maximisation of green appraisal score, to select preferred suppliers for green supply chains for a Taiwanese electronics company. Two GAs were used to obtain a set of Pareto-optimal solutions to solve the MOP model. Sadeghieh et al. (2012) proposed a GA based on grey goal programming to treat qualitative and quantitative attributes in solving a SES problem for a coffee maker machine manufacturing company. Rezaei and Davoodi (2012) proposed multi-objective nonlinear programming to optimise three objective functions, which were total profit, total inconsistency (late and wrong deliveries) and total deficiency (defective items), and to solve a multiple-item and multiple-period SES problem. In their study, GA was used to obtain a set of Pareto-optimal solutions to solve this multi-objective nonlinear programming problem. Gorji et al. (2014) developed an MINLP which considered multiple periods and products to determine optimal order quantities. The MINLP programming problem was solved by using GA. Aliabadi et al. (2013) proposed nonlinear binary programming to consider inventory costs for both suppliers and buyers, production costs for suppliers, and transportation costs in a multi-item environment. GA was used to solve this model to select the best supplier. Feng et al. (2011) proposed a multi-objective 0–1 integer programming approach to optimise three objective functions, which were the minimisation of service sourcing costs, the minimisation of service waiting time, and

the maximisation of collaborative utility, to solve a SES problem for a transportation firm. A multi-objective algorithm based on TS was utilised to solve multi-objective 0–1 integer programming problems. GA has also been combined with other AIMs (Artificial Bee Colony, Chaotic Bee Colony and Cuckoo search). For example, Jain et al. (2013) developed an MINLP model to consider all unit discounts and incremental discounts to minimise the total cost of the whole supply chain. This model was solved by using GA, Artificial Bee Colony, and Chaotic Bee Colony and the results of these methods were compared. Moreover, Kanagaraj et al. (2014) integrated reliability-based TCO and cuckoo search hybridised GA to solve a SES problem. In this study, reliability-based TCO accounting for both direct and indirect costs was fitted in nonlinear integer programming. A cuckoo search hybridised GA was used in the nonlinear integer programming model. Even though AIMs are highly useful for solving supplier selection problems, the interpretation of the decision logic of these models can be difficult for practitioners.

2.8 Models Aimed at Dealing with Uncertainty in Supplier Selection

There are two major approaches to handling variability (uncertainty) in quantitative data in the SES problem. They are fuzzy mathematical programming (Fuzzy MP) and stochastic mathematical programming (Stochastic MP). Most papers in the literature have used Fuzzy MP models to evaluate the performance of suppliers and to allocate orders to preferred suppliers. By comparison, the use of Stochastic MP in SES models is limited. In this section, the use of these two major techniques will be discussed in some detail.

2.8.1 Fuzzy Mathematical Programming

Fuzzy Mathematical Models have been extensively used to handle variability (uncertainty) associated with quantitative data used in solving supplier selection

problems. Kumar et al. (2004) used fuzzy GP (FGP) to minimise three objective functions, which were the net cost, the number of rejected items, and the number of late delivered items, as part of solving SES problem for an automobile company. In another model Kumar et al. (2006) applied fuzzy linear programming (FLP) to minimise similar objective functions to solve a SES problem in an uncertain environment for an automobile company. Compared to the study of Kumar et al. (2006), Amid et al. (2006) developed a weighted FLP to separate satisfaction degrees for each fuzzy objective functions, and fuzzy constraints to optimise three objective functions (minimisation of cost, maximisation of quality level and maximisation of service level), leading to the selection of preferred suppliers and allocating orders among them. Amid et al. (2009) also proposed using FLP with a weighted additive model to minimise three objective functions, which were the net cost, number of rejected items, and the number of late delivered items, while satisfying capacity and demand constraints to deal with supplier selection under price breaks. Additionally, Wu et al. (2010) developed a FLP which considered both qualitative and quantitative criteria to solve a SES problem. In this study, a possibility approach was used in the FLP model to optimise five objective functions which were the minimisation of total purchase price, minimisation of late delivered items, minimisation of rejected items, minimisation of risk factors of economic environment and minimisation of risk factors of vendor rate. Ozkok and Tiryaki (2011) proposed a compensatory FLP to allow efficient computation of the satisfaction levels of the objective function to select preferred suppliers and allocate order quantities in solving the multiple-item SES problem for a textile company. Arikan (2013) examined how FLP can enable decision-makers to obtain their preferred satisfaction levels for the objective function when solving the SES problem. Fuzzy Linear Programming (FLP) has been combined with AHP in some studies in order to

account for qualitative data in solving the SES problem. For example, Özgen et al. (2008) integrated AHP and possibilistic linear programming (PLP) to consider both qualitative and quantitative data to select preferred suppliers and to allocate orders for these suppliers. In their study, AHP was used to evaluate the performance of suppliers with respect to qualitative criteria to obtain scores for each supplier. These scores were then transferred into PLP as coefficients; to maximise one of the three objective functions, and to minimise the other objective functions, in selecting preferred suppliers. Although the above study proposed a comprehensive approach to solve the SES problem, the values of beneficial and non-beneficial criteria were not considered explicitly. The separation of beneficial and non-beneficial criteria is important as beneficial criteria should be maximised and non-beneficial criteria should be minimised. Sevkli et al. (2008) combined AHP and FLP to solve a SES problem for a Turkish TV manufacturer. In this study, AHP was used to assign scores for each supplier with respect to each criterion used. Then, these scores were transferred into FLP as coefficients of the six objective functions used (performance assessment, human resources, quality system assessment, manufacturing criteria, business criteria, information technology). Additionally, AHP was used to assign weights to the objective functions used in the additive model to select suppliers and allocate orders. Wang and Yang (2009) combined FLP, compromise programming and AHP to consider quantity discounts to solve the SES problem. In this study, compromise programming and AHP were used to assign weights to objective functions and FLP was used to select preferred suppliers and allocate orders. Amid et al. (2011) also integrated FLP and AHP to optimise similar objective functions and to select preferred suppliers in an uncertain environment. In this study, AHP was used to assign weights to each objective function. In addition, the results generated using AHP weighted FLP, additive weighted FLP and

weightless FLP were compared to identify more accurate results. In another study, Babić and Perić (2014) integrated AHP, simple additive weighting (SAW) and FLP to account for volume discounts in solving a SES problem for a bakery products manufacturer. AHP and SAW were used to determine scores for suppliers against complex criteria functions (quality and reliability). Then, these scores were transferred into FLP as coefficients of objective functions. FLP has been combined with other techniques such as fuzzy AHP, ANP, SWOT, TOPSIS and fuzzy concepts to handle imprecise data associated with human judgement, in many studies. For example, Yu et al. (2012) developed an integrated model, which considered time-based performance metrics for the SES problem, including fuzzy AHP to assign weights to objective functions and FLP to select preferred suppliers and to allocate order quantity in lean procurement environments for a stereo manufacturer. Lin (2012) developed a model including FANP and FLP to consider dependence (inner and outer dependence) and feedback between criteria to determine optimal order quantities for suppliers. In this study, FANP, consisting of fuzzy preference programming and ANP, was used to identify top suppliers and to consider inconsistent and uncertain judgements in pair-wise comparison matrices. FANP was then combined with FLP to select preferred suppliers and to allocate order quantities. Amin et al. (2011) combined fuzzy SWOT and FLP to consider particular strategies pursued by a company to solve a SES problem for an automobile company. In this study, fuzzy SWOT was used to assign scores for suppliers. These scores were then inserted into FLP as coefficients of an objective function to maximise certain attributes while satisfying the order requirement fuzzy demand constraint to select the best suppliers. In another study, Razmi et al. (2009) integrated FTOPSIS and FLP to consider a multi-period SES problem to determine optimal order quantities for a car product manufacturer. In the above study, FTOPSIS

was used to assign scores to each supplier with respect to qualitative criteria. These scores were then transferred into FLP as coefficients of one of four objective functions to allocate order quantities. In another study, Jadidi et al. (2014) proposed the normalised goal programming approach for crisp LP and FLP to obtain consistency levels among different objectives in supplier selection. In addition, they compared weighted goal programming, compromise programming, TOPSIS, weighted objectives, min-max goal programming and weighted max-min models to assess the effectiveness of normalised goal programming. Yücel and Güneri (2011) also integrated the fuzzy concept based on TOPSIS to identify weights of objective functions and FLP to determine optimal order quantities for selected suppliers. In the above study, the fuzzy concept was used to assign weights to each objective function in FLP. Haleh and Hamidi (2011) integrated fuzzy MCDM and FLP to handle the vagueness present in data and certain risks associated with supplier selection. In this study, fuzzy MCDM was used to assign weights to objective functions and FLP was used to optimise three objective functions, which were minimisation of price, maximisation of quality level and minimisation of risk, to determine optimal order quantity. FLP has also been combined with chance-constrained programming to handle uncertainty comprehensively. For example, Aghai et al. (2014) proposed a mixed-integer derivative nonlinear program to consider qualitative data, quantitative data and risk factors in a quantity discount environment to deal with supplier selection issues for an aeroplane company. This model was developed by combining FLP and chance-constrained programming.

Apart from FLP, fuzzy MCGP has been used to handle uncertain quantitative data. For example, Lee et al. (2009) proposed a model including fuzzy MCGP (FMCGP) and FAHP to solve a SES problem for downstream companies which were

selecting thin film transistor liquid crystal displays. In the above study, FAHP was utilised to assign weights to goals in FMCGP was used for allocating orders.

Overall, some studies have considered the variability associated with quantitative data (Kumar et al., 2004; Amid et al., 2006; Kumar et al., 2006; Arikan, 2013), whereas others have used weights for assigning varying degrees of importance to objective functions (Amid et al., 2011; Yücel and Güneri, 2011). Although these studies have proven to be efficient in solving the SES problem, they do not consider qualitative criteria/data, which are an important part of solving the SES problem. Therefore, some studies have considered qualitative and quantitative data in solving the SES problem (Özgen et al., 2008; Wu et al., 2010; Lin, 2012). These studies do not consider the multi-period SES problem; however, the demands of the buyer company may vary over time. Therefore, some studies have proposed models suitable for solving the multi-period SES problem (Razmi et al., 2009). Again, these studies do not consider discounts applicable to the SES problem; however, suppliers may offer discounts (volume, quantity and bundling). Some studies have considered discounts in the SES problem (Aghai et al., 2014; Babić and Perić, 2014). Most of these studies do not cover the pre-selection phase of the SES process.

Overall, the major limitations of current SES research, as reported in the literature, include: a lack of methods supporting the early stages of the SES process; a lack of methods suitable for service and public sector applications; and a lack of attention to emerging perspectives such as buyer-supplier relationships, design collaboration, e-procurement and supply chain security in the SES process (De Boer et al., 2001; Sonmez, 2006; Aissaoui et al., 2007; Jain et al., 2009) . There is a strong need for more comprehensive models and techniques which systematically combine

qualitative and quantitative criteria/data and consider multi-periods, discounts (especially bundling discounts) and the pre-selection phase of the SES process.

2.8.2 Stochastic Mathematical Programming

Stochastic approaches, which are capable of handling uncertainty, have been integrated with mathematical models (to be used in situations where historical data is available) to provide more robust and effective solutions than fuzzy approaches. Xu and Ding (2011) developed a bi-random chance constrained MOP to solve the SES problem under stochastic demand by using bi-random simulation-based GA. In another study, Kara (2011) integrated FTOPSIS and two-stage stochastic programming to solve a SES problem under stochastic demand conditions for a paper production company. This integrated model represented three phases, which were the pre-research phase, the pre-evaluation phase and the evaluation phase. Suppliers in the market, selection criteria and the system components were determined in the pre-research phase. FTOPSIS was used to rank suppliers with respect to qualitative attributes in order to determine the highest-ranking supplier group. Two-stage stochastic programming was used to evaluate the performance of the highest-ranking supplier group under stochastic demand. Li and Zabinsky (2011) also proposed a two-stage approach consisting of stochastic programming and chance constrained linear programming (CCLP) to consider volume discounts to determine optimal order quantities. Two-stage stochastic programming utilising penalty coefficients was used in a scenario-based model. CCLP considered probability distributions in capacity and demand constraints. Zhou et al. (2011) developed an integer-valued inventory in a stochastic dynamic programming approach to consider finite horizon planning under stochastic demand. A heuristic approach was used in their study to solve stochastic dynamic programming. Zhang and Zhang (2011) proposed a mixed-integer programming model to solve a SES problem

under stochastic demand. This model used the branch-bound algorithm. Yang et al. (2011) also integrated a stochastic model and GA for selecting suppliers under stochastic demand. The stochastic model solved by GA was used to maximise expected profit while satisfying the requirements of service levels and budget constraints. In another study, Bilsel and Ravindran (2011) used CCLP to solve supplier selection problems in uncertain environments. CCLP was used to consider multi-period planning and multi-product ordering in order to minimise stochastic cost, maximise quality level and minimise lead-time, while satisfying stochastic demand and stochastic capacity. CCLP was undertaken by using non-pre-emptive GP. Guo and Li (2014) developed an MINLP model to consider a multi-echelon system in a stochastic demand environment to solve a supplier selection problem, as well as inventory level problems in a serial supply chain system. This model was used to determine preferred suppliers and the replenishment decisions for maintaining desired inventory levels. Meena and Sarmah (2014) proposed an MINLP-based approach which took into account different failure probabilities, capacities, price discounts and compensation potentials under stochastic demand to select preferred suppliers. Real coded GA was used in this model.

Overall, most of the studies reviewed above have only considered the variability associated with quantitative data. However, qualitative data plays an important part in solving the SES problem. Some studies considered the role of discounts in the SES problem (Li and Zabinsky, 2011; Meena and Sarmah, 2014). Additionally, some studies have considered multi-periods and inventory levels (Bilsel and Ravindran, 2011; Guo and Li, 2014). Moreover, Kara (2011) proposed a pre-selection phase to reduce supplier numbers. There is still a research gap with respect to the comprehensiveness of the models discussed above, in terms of their coverage of multi-periods, discounts, pre-

selection and qualitative criteria/data situations. Additionally, most of the studies only consider fuzzy or stochastic data to address uncertainty issues in the SES problem.

2.9 Empirical Validation of SES Models

Several studies reported in the literature have attempted to validate supplier selection models in numerous ways. These studies have also pursued different approaches to evaluate the efficacy of the proposed models. For example, Jayaraman et al. (1999) and Dahel (2003) suggested experimental designs to validate their SES models. The former varied the number of suppliers, the number of products and the demand level to validate their model with experiments, whereas the latter varied the number of items, the number of vendors, the number of discount brackets and the number of plants in validating their model with experiments. Aguezzoul and Pierre (2004), on the other hand, applied a scenario-based validation approach for evaluating the effectiveness of a nonlinear multi-objective programing model in solving a supplier selection problem involving transportation costs in two situations, namely less than truck load and truck load. Kull and Talluri (2008) integrated AHP to derive risk scores with respect to risk dimensions (delivery failure, cost failure, quality failure, flexibility failure, general confidence failure) and GP to mitigate these risk scores in dealing with supply risk issues and to consider product life cycle phases in solving a SES problem for a precision turned steel producer. The authors tested the efficacy of their models using different scenarios. Wu (2009b) used the k-fold cross validation technique to evaluate their model by using a small set of data. In this approach, the data set was divided into k, which was an integer, subsets and the model was run for k times in DT and NN. Golmohammadi et al. (2009) integrated GA to identify initial weights and the architecture of the network and NN to model the SES problem. The authors compared the results of their model with the rankings of suppliers provided by two practising

managers to validate their model. Vinodh et al. (2011) used FANP to select preferred suppliers for an electronics company. In this study, the authors used questionnaire-based validation to assess the feasibility of FANP. In an attempt to evaluate the efficacy of their model, Golmohammadi and Mellat-Parast (2012) applied two hypotheses to assess the usefulness of the grey model they proposed, which was compared with the grey model used in the literature. In this case, the authors used the t-test to highlight the difference between their grey model and the grey model used in the literature. Even though most of the models developed in these studies have been validated using statistical techniques, experiments and questionnaires, they have not accounted for qualitative data, or for the variability associated with quantitative data, in their proposed models. Therefore, there is still a need for empirically testing SES models that account for both qualitative data and the variability associated with quantitative data. Moreover, there have been a number of studies reported in the literature (referred to in previous sections) that have developed SES models aimed at specific industry applications (those referred in previous sections). However, only a very few of them have used empirically derived data to test their models (Çelebi and Bayraktar, 2008; Sevkli, 2010; Feng et al., 2011). However, these studies do not consider qualitative data and the variability associated with quantitative data together in solving the SES problem. Table 2.1 indicates summary of key literature used in this thesis.

Table 2.1: Summary of Key Literature

Authors	Methods	Criteria
Chan and Kumar (2007)	FAHP	• Overall cost of the product • Quality of the product • Service performance of supplier • Supplier's profile • Risk factor
Ha and Krishnan (2008)	AHP, DEA and NN	• Quality • Delivery • Management and Organization

Özgen et al. (2008)	AHP and PLP	• Delivery Reliability • Flexibility and Responsiveness • Cost • Assets • Environmental Responsiveness • Uncertain Cost • Uncertain Defect Percentage • Uncertain Demand
Kull and Talluri (2008)	AHP and GP	• Delivery Failure • Cost Failure • Quality Failure • Flexibility Failure • Confidence Failure
Amid et al. (2009)	FLP	• Uncertain Cost • Uncertain Defect Percentage • Uncertain Late Delivery Percentage • Uncertain Demand
Wu et al. (2009)	ANP and MILP	• Management Quality • Technical Quality • Operational Quality • Fixed Cost • Variable Cost
Kara (2011)	FTOPSIS and Two-stage Stochastic Programming	• Cost • References • Quality of the product • Delivery Time • Institutionality • Execution time • Uncertain Cost • Defect Percentage • Late Delivery Percentage • Demand
Bilsel and Ravindran (2011)	CCLP	• Uncertain Cost • Uncertain Demand • Quality of the product • Lead Time • Uncertain Capacity
Li and Zabinsky (2011)	Stochastic Programming and CCLP	• Cost • Uncertain Demand • Quality of the product • Late Delivery • Uncertain Capacity
Vinodh et al. (2011)	FANP	• Business Improvement • Extent of Fitness • Quality • Service • Risks
Lin (2012)	FANP and FLP	• Price • Technique • Quality • Delivery • Uncertain Cost • Uncertain Demand • Uncertain Delivery • Uncertain Quality
Babić and Perić (2014)	AHP, SAW and FLP	• Cost • Reliability • Quality

Aghai et al. (2014)	Mixed-integer Derivative Nonlinear Program	• Uncertain Cost • Uncertain Defect Percentage • Uncertain Late Delivery Percentage • Uncertain Demand • Environment Risk • Vendor Rate

2.10 Research Gaps

Based on the above literature review the following research gaps concerning the SES problem are identified:

- Most of the studies in the literature have proposed models for the manufacturing industry, with a few exceptions in which the service and public sector applications have been considered (De Boer et al., 2001; Sonmez, 2006). Therefore, there is a lack of research examining the SES problem in the context of service and public sector organisations. This gap will not be addressed in this thesis and can be of interest for future studies.
- The literature review also highlights a general lack of attention to emerging perspectives such as buyer-supplier relationships, design collaboration, e-procurement and supply chain security in the SES process (Sonmez, 2006; Aissaoui et al., 2007; Jain et al., 2009). This could, however, be partly due to the fact that these areas are still relatively new. This gap will not be addressed in this thesis and can be of interest for future studies.
- Another major criticism of SES research found in the literature is a lack of models supporting the early stages of the SES process; that is, the screening and pre-selection stages have not been incorporated into most SES models. In cases where there are a large number of candidate suppliers, pre-selection can be used to bring that number down to a manageable level before they are evaluated more

comprehensively. There have been a few studies considering the pre-selection phase of the SES process (Mendoza et al., 2008; Kara, 2011).

- Even though many studies have developed models capable of solving the SES problem by considering both qualitative and quantitative data in comprehensive and systematic ways, these models have rarely been subject to empirical validation. Empirical validation indicates the usefulness and the feasibility of a model from an industry application perspective. In the limited number of studies that have validated their models using questionnaires or statistical techniques (those referred to in Section 2.9) the models themselves have not incorporated qualitative data and the variability associated with quantitative data.
- Some studies have also considered the impact of transportation alternatives in selecting suppliers (Songhori et al., 2011; Arabzad et al., 2015). However, again, most of these studies have not accounted for qualitative data and the variability associated with quantitative data in their models. Therefore, there is an opportunity to develop a comprehensive model that accommodates qualitative data, the variability associated with quantitative data, and transportation costs in solving the SES problem.
- Most of the studies reviewed above do not consider the effects of bundling discounts in supplier selection decisions. The very few studies that have considered bundling discounts (Omid et al., 2008; Wu et al., 2009) have not accounted for the variability associated with quantitative data.
- In terms of dealing with the effects of uncertainty and variability on supplier selection decisions, most of the models have only considered fuzzy (Kumar et al., 2004; Amid et al., 2006; Kumar et al., 2006) or stochastic (Bilsel and Ravindran, 2011; Guo and Li, 2014) data. Although these models are considered

to be sufficient for handling the uncertainty associated with quantitative data, their application can be restricted by the lack of availability of both fuzzy and stochastic data in practice.

Even though this thesis highlights some of the most important gaps in SES literature, literature gaps 1 and 2 will not be addressed in this thesis. These gaps can be considered in future studies. Other gaps (3-7) will be addressed in this study. All in all, the major gaps in current SES research identified through the review of literature point to the need to develop more comprehensive SES models that: account for the full scope of the SES problem; can efficiently handle both qualitative and quantitative data; can deal with the variability associated with quantitative data and ambiguity around qualitative data; and can accommodate the demands posed by varying situational requirements. Moreover, there is a need for empirical validation of models. Additionally, in light of the plethora of techniques, models and frameworks that have been proposed in the literature, there is a strong requirement for the complexity of any new models developed to be commensurate with the demands of practitioners. That is, these models should be sophisticated enough to address the issues discussed above, but at the same time palatable to the decision-makers in terms of the knowledge and skill levels required for them to use the models with relative ease.

2.11 Summary

In global competitive markets, the buyer company strive to meet dynamic customer requirements while at the same time minimising the total costs of their business operations. Supplier selection is one of the key areas in which there is a significant opportunity to meet customer requirements while at the same time driving down total supply chain costs. This chapter examined the key perspectives of supplier selection in order to identify the key challenges and opportunities for enhancing

supplier selection decisions. This was followed by a comprehensive evaluation of the key elements of the supplier selection process, including selection criteria, and the range of methods and models used. In particular, the most current and integrated models of SES were examined in detail in order to assess their merits and limitations.

A key finding of the literature review is that, although there is a wide range of techniques, models and frameworks that can potentially be very useful for supporting supplier selection decisions, there are a number of issues associated with their utility. In particular, there the review found no adequate evidence in the literature to support their widespread application in the industry. This situation, along with the research gaps identified through the review of literature, highlights the need to develop new models that can overcome the challenges outlined above.

3 DEVELOPMENT OF THE FUZZY INTEGRATED MODEL

3.1 Introduction

In this chapter, capability-based risks and performance-based risks are analysed and treated towards solving the supplier evaluation and selection (SES) problem. The set of sub-criteria selected under each of these risk categories were commonly cited in literature. The two types of risks, capability-based and performance-based risks, are analysed using two main types of data, which are qualitative and quantitative. Moreover, the selected sub-criteria are only sample criteria and additional criteria can be easily added to be treated by the proposed models, as needed, with no modifications to the tools and techniques used.

The capability-based risks are considered as qualitative criteria, which are difficult to quantify. These risks are examined in this thesis include following main criteria:

Financial Position: The financial status of the supplier in the market in terms of its assets and liabilities. Financial stability of suppliers is an important necessity for the buyer company to build, maintain and sustain a long-term partnership between the buyer company and suppliers. Therefore, financial position of suppliers is a relevant indicator of the supplier's capability to support a long term relationship with the manufacturer.

Volume Flexibility: The ability of a supplier's manufacturing process to handle large variations in volume without significant changes in time and facility requirements. Volume flexibility meets the requirement of the buyer company in time by matching demand with supply. Thus, the lack of volume flexibility may deteriorate the situation of the buyer company in case of urgent demand fluctuations.

Technological Capability: The supplier's ability to adopt high-end technologies in its manufacturing processes. On the one hand, advancements in technology allows manufacturers to demand high quality low cost products from suppliers. On the other hand suppliers tend to develop and adopt high-end technologies to increase the performance of their products to satisfy the needs of the buyer company and stay competitive. Therefore, technological capability is another important factor for both supplier and the buyer company.

Reputation: The supplier's position (compared to competitors) in the industry including product leadership and brand image. Suppliers should have good commercial relationships with buyer companies in the market, including the adherence to mutually beneficial trade terms and good etc.. Additionally, suppliers should have good business references from buyer companies and they should have a good customer base.

Compliance with Sectoral Price: The supplier's purchasing price of items not being over the market average. The buyer company always looks for minimum price of items and market average price is an indicator that the price of items is cheap or expensive. Therefore, suppliers should keep their price of items in market average.

Communication Issues: Lack of communication between the manufacturer and the supplier in relation to information exchange about the procured items. Good communication between the manufacturer and the supplier can help develop long-term relationships. Cultural differences, ethics differences and language difficulties in communication between the manufacturer and the supplier can lead to the deterioration of relationships, so communication issues should be minimised to maintain good relationships.

Performance-based risks prevent the achievement of the short term goals of the buyer company. Performance-based risks analysed can occur in the following areas:

Uncertain Total Cost: Variability in the sum of purchasing price, transportation costs and ordering costs. Minimum allowable total cost is important for the buyer company to maintain their profitability. Therefore, the buyer company endeavours to establish a low total cost supply base.

Uncertain Defect Percentage: Variability in the percentage of defective items received. Items which have some quality problems, such as torn fabric and knots, which are caused by the yarn's tying spools together, are defective items and these items are rejected by the buyer company in period.

Uncertain Late Delivery Percentage: Variability in the percentage of items received later than the promised delivery date. Late delivered items negatively impact on production schedules and could increase machine idle times and underutilised resources. Therefore, the number of late delivered items should be minimised by the manufacturer.

Uncertain Order Requirement: Variability about the required quantities the buyer company needs from suppliers for a year. Order requirement of the buyer company can easily change annually or periodically (monthly or daily) as it depends on the demand of company.

Uncertain Production Capacity: Maximum number of items can be produced by a supplier in a year that can be purchased by the buyer company. Production capacity of suppliers can vary annually or periodically. Therefore, the production capacity of suppliers is treated as a fuzzy attribute (in Chapter 3 and 4), as well as a stochastic attribute (in Chapter 5).

The performance-based risks include variability in quantitative data which can be modelled/analysed using uncertainty analysis techniques such as fuzzy sets or probability distribution functions. In Chapters 3 and 4, performance-based risks are

analysed based on fuzzy set theory; and in Chapter 5, performance-based risks are modelled using fuzzy sets and stochastic probability distributions.

Most of the studies in this area have attempted to mitigate operational risks by considering quantitative data (related to performance-based risks) while neglecting qualitative data (related to capability-based risks) (Bilsel, 2009; Bilsel and Ravindran, 2011). Some studies have taken into account capability-based risks in supplier selection without considering performance-based risks (Chan and Kumar, 2007). There are other studies (Özgen et al., 2008; Lin, 2012) which have solved the general SES problem, however these studies do not apply those models in practice and do not measure the feasibility of models. The proposed model in this chapter considers qualitative and quantitative data and the feasibility of this model is measured in practice.

This chapter is organised as follows. Section 3.2 provides the supplier selection criteria used in the proposed fuzzy integrated model. Section 3.3 discusses the analysis of capability-based risks using FAHP and COPRAS-F. Section 3.4 discusses the analysis of performance-based risks and the results of the model. Section 3.5 provides a brief summary of the chapter.

3.2 Fuzzy Integrated Model

A fuzzy integrated model (FIM) is proposed to mitigate both performance-based risks (quantitative) and capability-based risks (qualitative) in this chapter and Chapter 4. The proposed model (a fuzzy integrated model), illustrated in Figure 3.1, is used to evaluate potential suppliers in terms of both performance-based (quantitative) risks and capability-based (qualitative) risks either sequentially or concurrently – which means the FIM provides the decision-maker with a degree of flexibility in terms of using it in the screening and/or evaluation phases of the supplier evaluation and selection process. Information on decision-makers' judgements about the relative importance of

performance-based risks and capability-based risks, solicited through a questionnaire survey, is used as input to the FIM. The process starts with the analysis of capability-based risks (qualitative criteria) such as financial position, volume flexibility, technological capability and reputation of the supplier, against capability-based risks, using fuzzy analytic hierarchy process (FAHP) (Calabrese et al., 2013) and fuzzy complex proportional assessment (COPRAS-F) techniques (Zavadskas and Kaklauskas, 1996), in Step 1 and Step 2 of FIM respectively. FAHP is used to establish the relative importance of capability-based risks (qualitative criteria) used, by assigning a weight to each criterion based on the judgement of the decision-maker. COPRAS-F is used to evaluate each supplier against the capability-based risks (qualitative criteria) used, in the form of scores assigned by the decision-maker based on historical data or expert judgement. The resultant aggregate weighted scores (representing all capability-based risks) are used as objective function coefficients in the fuzzy linear programming (FLP) model, in step 5. In cases where there is a large number of candidate suppliers, these aggregate scores can also be used to bring that number down to a manageable level (i.e. screening/pre-qualification) before they are evaluated against capability-based risks.

The analysis of performance-based risks (quantitative criteria) is undertaken in such a way that any variability associated with supplier performance is also built into relevant metrics as appropriate. For instance, performance-based risks (quantitative criteria) are first defined as uncertain cost, late delivery percentage and defect percentage, which are then measured using fuzzy numbers. Additionally, supplier production capacity is also identified at this stage and this data is later fed into the FLP model (Step 5) in the form of a constraint. Furthermore, given that data in relation to performance-based risks are represented as fuzzy numbers in the survey dataset, in step 3, they are converted into crisp numbers using the signed distance method (see Section

3.4.1) so that they can be used in the FLP model in the form of weights of the objective function in Step 5.

In Step 4 of the process, FAHP is employed again to establish the relative importance of all risks used: that is, each of the performance-based risks along with one aggregate measure representing all capability-based risks (derived in Step 2). The weights representing the relative importance of these risks are used as objective function coefficients in the FLP model.

This FLP model is finally solved, by using Lindo 15, for supplier selection and order allocation among those selected suppliers using the max-min method (see Step 5). Lindo 15 is a comprehensive optimization software to build and solve linear and nonlinear models and this software uses C++ codes to solve models with loop.

Table 3.1 shows the notations used in the proposed fuzzy integrated model.

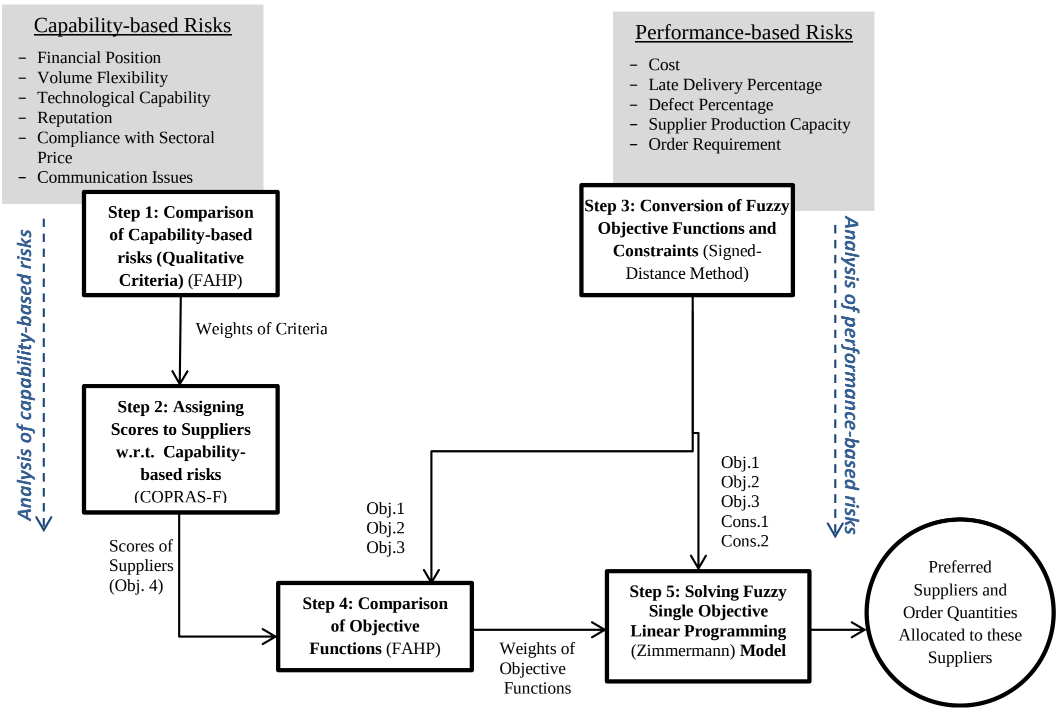

Figure 3.1: The proposed FIM module for supplier selection and order allocation

Table 3.1: Notations

Parameters	Definition
$\tilde{B}, B$	Fuzzy and crisp decision matrix to compare criteria

$\tilde{b}_{ij}$, b_{ij}	Element of fuzzy decision matrix ($\tilde{B}$, B)to compare criteria
$l(.)$	The lower point of any fuzzy numbers
$m(.)$	Medium point of any fuzzy numbers
$u(.)$	The higher point of any fuzzy numbers
n	Total number of qualitative criteria
b_{ij}	Crisp score using to obtain Consistency Index (CI)
β_{max}	Largest eigenvalue of the comparison matrix
$\widetilde{RS}_i$	Relative row sum for $\tilde{B}$
$\widetilde{w}_i/w_i/w_i^*$	Fuzzy/crisp/normalised weights of i^{th} criteria
$\tilde{F}$	Fuzzy decision matrix to evaluate supplier performance
$\tilde{f}_{si}$	An element of fuzzy decision matrix ($\tilde{F}$) to evaluate supplier performance
F	Crisp decision matrix to evaluate supplier performance
f_{si}	A crisp element of crisp decision matrix (F)
F^*	Normalised decision matrix
f_{si}^*	An element of normalised decision matrix (F^*)
F'	Weighted normalised decision matrix
f'_{si}	An element of weighted normalised decision matrix (F')
K_s^+	The sum value of s^{th} supplier w.r.t beneficial criteria
K_s^-	The sum value of s^{th} supplier w.r.t non-beneficial criteria
t	Total number of suppliers $\left(s \in (1,2,3 \ldots t)\right)$
o	Total number of beneficial criteria of s^{th} supplier
i	Showing the criteria number w.r.t row in $\tilde{B}$
j	Showing the criteria number w.r.t column in $\tilde{B}$
Q_s	The relative importance of s^{th} supplier
Q_{max}	Maximum relative importance
U_s	Utility score or final score of s^{th} supplier
$\tilde{Z}_1/Z_1$	Fuzzy/crisp total purchasing cost objective function
$\tilde{Z}_2/Z_2$	Fuzzy/crisp late delivered unit objective function
$\tilde{Z}_3/Z_3$	Fuzzy/crisp defective unit objective function
Z_4	Crisp value for total purchasing objective function
X_s	Order quantity for s^{th} supplier
$\tilde{P}_s/P_s$	Fuzzy/crisp purchasing price for s^{th} supplier
$\widetilde{TC}_s/TC_s$	Fuzzy/crisp transportation cost for s^{th} supplier
$\tilde{L}_s/L_s$	Fuzzy/crisp late delivery percentage for s^{th} supplier
$\widetilde{DP}_s/DP_s$	Fuzzy/crisp defect percentage for s^{th} supplier
$\widetilde{V}_s/V_s$	Fuzzy/crisp supplier production capacity for s^{th} supplier
OR	Total order requirement of manufacturing company
T_s	Numbers of truck available for s^{th} supplier
p_s	Capacity of truck transporting material from s^{th} supplier
Y_s	Decision variable {0,1}
λ_y	Satisfaction degree for y^{th} objective function
h_y	Weight for y^{th} objective function
c	Total number of objective functions
λ_k	Satisfaction degree for k^{th} minimising objective function
λ_z	Satisfaction degree for z^{th} maximising objective function
Z_k^-	Minimum value of k^{th} objective function
Z_k^+	Maximum value of k^{th} objective function
Z_z^-	Minimum value of z^{th} objective function
Z_z^+	Maximum value of z^{th} objective function
$\mu_k\left(Z_k(x)\right)$	Linear Membership for Maximisation of k^{th} objective function
$\mu_z\left(Z_z(x)\right)$	Linear Membership for Minimisation of z^{th} objective function
N	Total number of Minimisation objective functions

G	Total number of Maximisation objective functions

3.3 Analysis of Capability-based Risks (Qualitative Criteria)

In this section, we describe the process followed in the analysis and evaluation of the capability-based risk of suppliers that are measured qualitatively. FAHP is employed to establish the relative importance of the capability-based risks used by assigning weights to each capability-based risk, whereas COPRAS-F is used to evaluate suppliers against capability-based risks.

3.3.1 Comparison of Capability-based Risks (Qualitative Criteria) (Step 1)

The analysis and comparison of capability-based risks (qualitative criteria) is carried out using FAHP in Step 1. Here, the normalisation formula suggested by Wang et al. (2008) is employed to overcome the limitations of the extent to which analysis used in the previous FAHP reported in Chang (1996). The sub-steps of FAHP used in this step of the qualitative evaluation process are detailed below:

Step 1.1: The judgements of decision-makers which are expressed in linguistic terms based on the pair-wise comparison of qualitative criteria (capability-based risks) are first converted into triangular fuzzy numbers (TFNs) using the fuzzy weights provided in Table 3.2.

Table 3.2: Linguistic scores and fuzzy weights used for the comparison of qualitative criteria

Linguistic Scores	Fuzzy Weights
Extremely Important	(7/2,4,9/2)
Very Important	(5/2,3,7/2)
Important	(3/2,2,5/2)
Moderately Important	(2/3,1,3/2)
Equally Important	(1,1,1)

In order to compare qualitative criteria, these TFNs are then organised into a fuzzy decision matrix as follows:

$$\tilde{B} = \left(\tilde{b}_{ij}\right)_{n\times n} \tag{1}$$

where

$$\tilde{b}_{ij} = \left(l(\tilde{b}_{ij}), m(\tilde{b}_{ij}), u(\tilde{b}_{ij})\right) \; and \; \tilde{b}_{ij}^{-1} = \left(\frac{1}{l(\tilde{b}_{ij})}, \frac{1}{m(\tilde{b}_{ij})}, \frac{1}{u(\tilde{b}_{ij})}\right) \; i,j = 1, \dots n; i \neq j \quad (2)$$

and $l(\tilde{b}_{ij}), m(\tilde{b}_{ij})$ and $u(\tilde{b}_{ij})$ represent the lower, medium and upper values of $\tilde{b}_{ij}$ respectively. To analyse the consistency of each pairwise comparison in $\tilde{B}$, a consistency index (CI) and consistency ratio (CR) are calculated following Eqns. 4 and 5 respectively (Kwong and Bai, 2003). If the calculated CR of $\tilde{B}$ is less than 0.1, the consistency of $\tilde{B}$ is accepted. Otherwise, the pair-wise comparison of decision-makers' judgements used to generate $\tilde{B}$ is deemed inconsistent and a new pair-wise comparison must be undertaken. To calculate CI, each $\tilde{b}_{ij}$ is first converted into crisp numbers using the centre of gravity method (Yager, 1981; Wang and Elhag, 2007):

$$b_{ij} = \frac{l(\tilde{b}_{ij}) + m(\tilde{b}_{ij}) + u(\tilde{b}_{ij})}{3} \qquad i,j = 1, \dots n \quad (3)$$

Following the conversion of fuzzy numbers into crisp numbers, the largest eigenvalue of B (β_{max}) is calculated. This β_{max} is then used to calculate *CI* in Eqn. 4 followed by the calculation of CR using Eqn. 5. The $RI(n)$, used in Eqn. 5 is a random index based on n (Golden et al., 1989). Since, this study compares only 6 qualitative criteria (i.e. $n = 6$) and four objective functions (i.e. $n = 4$), Table 3.3 shows relevant *RI (n)* for $n = 6, 4$. *CI* and *CR* are computed as:

$$CI = \frac{(\beta_{max} - n)}{n - 1} \quad (4)$$

$$CR = (CI - RI(n)) \quad (5)$$

If $\tilde{B}$ is consistent, we continue the analysis of $\tilde{B}$ in Step 1.2. Otherwise, the querying process is repeated to obtain the preferences of decision-makers, until a consistent $\tilde{B}$ is achieved.

Table 3.3: Random index for calculating consistency index

n	4	6
$RI(n)$	0.9	1.24

Step 1.2: Relative row sum is calculated for each row in $\tilde{B}$ as:

$$\widetilde{RS}_i = \sum_{j=1}^{n} \tilde{b}_{ij} = \left(\sum_{j=1}^{n} l(\tilde{b}_{ij}), \sum_{j=1}^{n} m(\tilde{b}_{ij}), \sum_{j=1}^{n} u(\tilde{b}_{ij})\right) \qquad i,j = 1, \dots n \tag{6}$$

Step 1.3: The normalisation formula reported in Wang et al. (2008) is used to normalise relative row sums ($\widetilde{RS}_i$). The normalisation is shown as:

$$\widetilde{w}_i = \frac{\widetilde{RS}_i}{\sum_{j=1}^{n} \widetilde{RS}_i}$$

$$= \left(\frac{\sum_{j=1}^{n} l(\tilde{b}_{ij})}{\sum_{j=1}^{n} l(\tilde{b}_{ij}) + \sum_{q=1,q\neq j}^{n} \sum_{j=1}^{n} u(\tilde{b}_{qj})}, \frac{\sum_{j=1}^{n} m(\tilde{b}_{ij})}{\sum_{q=1}^{n} \sum_{j=1}^{n} m(\tilde{b}_{qj})}, \frac{\sum_{j=1}^{n} u(\tilde{b}_{ij})}{\sum_{j=1}^{n} u(\tilde{b}_{ij}) + \sum_{q=1,q\neq j}^{n} \sum_{j=1}^{n} l(\tilde{b}_{qj})}\right)$$

$$= \left(l(\widetilde{w}_i), m(\widetilde{w}_i), u(\widetilde{w}_i)\right) \qquad i,j = 1, \dots n \tag{7}$$

Step 1.4: TFNs for weight ($\widetilde{w}_i$), i.e., $(l(\widetilde{w}_i), m(\widetilde{w}_i), u(\widetilde{w}_i))$ for i^{th} criteria are converted into crisp weight (w_i) of i^{th} criteria by:

$$w_i = \frac{l(\widetilde{w}_i) + m(\widetilde{w}_i) + u(\widetilde{w}_i)}{3} \qquad i = 1,2, \dots . n \tag{8}$$

Step 1.5: Crisp weight (w_i) of i^{th} criteria is normalised by:

$$w_i^* = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad i = 1,2, \dots . n \tag{9}$$

3.3.2 Assigning Scores to Suppliers (Step 2)

After developing the normalised weights of each qualitative criterion (w_i^*), each supplier is assessed against the qualitative criteria using COPRAS-F approach (Step 2). The sub-steps involved in COPRAS-F are:

Step 2.1: Decision-makers' assessments of suppliers against qualitative criteria (in linguistics terms) are first converted into fuzzy scores using Table 3.4. These scores are then used in the fuzzy decision matrix ($\tilde{F}$) to develop utility degrees reflecting the aggregate scores for each supplier considering all the qualitative criteria used, as follows:

$$\tilde{F} = \left(\tilde{f}_{si}\right)_{t\times n} \qquad i = 1,2, \dots . n \qquad s = 1,2, \dots . t \tag{10}$$

where:

$$\tilde{f}_{si} = \left(l(\tilde{f}_{si}), m(\tilde{f}_{si}), u(\tilde{f}_{si})\right) \quad i = 1,2,\ldots.n \quad s = 1,2,\ldots.t \qquad (11)$$

Table 3.4: Linguistic and fuzzy scores used for the evaluation of suppliers against qualitative criteria

Linguistic Scores	Fuzzy Scores
Very High	(7,9,10)
High	(5,7,9)
Medium	(3,5,7)
Low	(1,3,5)
Very Low	(0,1,3)

Step 2.2: $l(\tilde{f}_{si}), m(\tilde{f}_{si}), u(\tilde{f}_{si})$ are fuzzy scores of the s^{th} supplier with respect to the i^{th} criteria and these scores are converted into crisp scores f_{si} for the s^{th} supplier with respect to the i^{th} criterion using:

$$f_{si} = \frac{l(\tilde{f}_{si}) + m(\tilde{f}_{si}) + u(\tilde{f}_{si})}{3} \qquad i = 1,2,\ldots.n \quad s = 1,2,\ldots.t \qquad (12)$$

Step 2.3: After fuzzy numbers are converted into crisp scores (f_{si}), a crisp decision matrix for evaluating suppliers (F) is obtained; each element of F matrix is normalised as follows;

$$f_{si}^{*} = \frac{f_{si}}{\sum_{s=1}^{t} f_{si}} \qquad i = 1,2,\ldots.n \quad s = 1,2,\ldots.t \qquad (13)$$

Step 2.4: After normalisation, each element in the normalised decision matrix (F^{*}) is multiplied by the normalised weights (w_i^{*}) calculated in Step 1 to obtain the weighted normalised matrix (F') as follows;

$$F' = [f'_{si}]_{t \times n} = f_{si}^{*} \times w_i^{*} \qquad i = 1,2,\ldots.n \quad s = 1,2,\ldots.t \qquad (14)$$

Step 2.5: The sums of values assigned to the beneficial and non-beneficial criteria for the s^{th} supplier (i.e. $K_s^{+}$and K_s^{-}) are derived separately from the weighted normalised matrix F' . The beneficial criteria are: financial position, volume flexibility, technological capability, reputation and compliance with sectoral price. The only non-beneficial criterion is communication issues. The beneficial criteria contribute positively toward achieving the overall goal of

supplier selection and are, therefore, maximised. Non-beneficial criteria are minimised as they have a negative impact on the overall goal of supplier selection. K_s^+ and K_s^- are calculated using the following equations:

$$K_s^+ = \sum_{i=1}^{o} f'_{si} \tag{15}$$

$$K_s^- = \sum_{i=o+1}^{n} f'_{si} \qquad i = 1,2, \dots .n \quad s = 1,2, \dots .t \tag{16}$$

Step 2.6: The relative importance (Q_s) of each supplier based on qualitative criteria is calculated using the following equation:

$$Q_s = K_s^+ + \frac{\sum_{s=1}^{t} K_s^-}{(K_s^- * \sum_{s=1}^{t} \frac{1}{K_s^-})} \qquad s = 1,2, \dots .t \tag{17}$$

Step 2.7: Finally, the value representing the relative importance of each supplier (Q_s) is divided by the value of maximum relative importance (Q_{max}) to obtain the final scores or utility score (U_s) of each supplier indicating the overall performance of suppliers against qualitative criteria as shown below:

$$U_s = (\frac{Q_s}{Q_{max}}) \qquad s = 1,2, \dots .t \tag{18}$$

These final scores are used in the FLP model as the weights of the objective functions, for the purpose of maximising the total score of suppliers (to mitigate capability-based risks) which also accounts for the order quantities allocated to each supplier, while considering their production capacity.

3.4 Analysis of Performance-based Risks (Quantitative Criteria)

In this section, the analysis of performance-based risks (quantitative criteria) is illustrated using four quantitative criteria: cost, delivery, quality and supplier production capacity. The quantitative criteria (performance-based risks) used are defined in such a way that they also account for the variability associated with supplier performance. The two techniques used in this part of the process are the signed distance method (Yao and

Wu, 2000; Zhou and Gong, 2004) and the max-min method (Zimmermann, 1978), the application of which is detailed below.

3.4.1 Conversion of Fuzzy Objective Functions and Constraints (Step 3)

This section details the conversion of the fuzzy values assigned by decision-makers in evaluating supplier performance into crisp numbers that can be incorporated into the FLP model. The fuzzy values (pessimistic, most probable and optimistic) can be derived based on historical data or expert judgement. The FLP model uses three fuzzy objective functions: minimisation of total purchasing cost; minimisation of the number of units delivered late; and minimisation of the number of defective units. The model uses one crisp objective function: maximisation of total score. Equation 19 represents the minimisation of total purchasing cost in which $\tilde{P}_s$ is the fuzzy purchasing price for the s^{th} supplier, $\widetilde{TC}_s$ is the fuzzy transportation cost for the s^{th} supplier, X_s is the order quantity for the s^{th} supplier and T_s, which is an integer, is the number of trucks available for the s^{th} supplier to supply the manufacturing company. If the company considers transportation costs in its supplier selection process, this equation will be used directly. However, if the company does not consider transportation costs in selecting its suppliers, transportation cost will be removed from this equation.

$$Min\ \tilde{Z}_1 = \sum_{s=1}^{t} \tilde{P}_s \times X_s + \sum_{s=1}^{t} \widetilde{TC}_s \times T_s \qquad s = 1,2, \dots .t \tag{19}$$

Equation 20 represents the minimisation of late delivered units where $\tilde{L}_s$ is the fuzzy late delivery percentage for the s^{th} supplier.

$$Min\ \tilde{Z}_2 = \sum_{s=1}^{t} \tilde{L}_s \times X_s \qquad s = 1,2, \dots .t \tag{20}$$

Equation 21 represents the minimisation of defective units where $\widetilde{DP}_s$ is the fuzzy defective percentage for the s^{th} supplier.

$$Min\ \tilde{Z}_3 = \sum_{s=1}^{t} \widetilde{DP}_s \times X_s \qquad s = 1,2, \dots .t \tag{21}$$

Additionally, there is a fuzzy constraint (supplier production capacity) in the FLP model. $\widetilde{V_s}$ represents the fuzzy supplier production capacity for the s^{th} supplier. This fuzzy constraint is defined as follows:

$$X_s \leq \widetilde{V_s} \times Y_s \qquad s = 1,2, \dots . t \tag{22}$$

These fuzzy objective functions and the constraints are converted into crisp numbers using signed distance method in Step 3 of the process. The signed distance method is used to convert fuzzy numbers into crisp numbers as defined by Zhou and Gong (2004). Given that $\tilde{e}$ is a fuzzy number and its fuzzy linear membership value is represented as $\mu_{\tilde{e}}(x) \in [0,1]$, the α-level, which is the fuzzy linear membership degree of crisp numbers of $\tilde{e}$, the set of $\tilde{e}$ is expressed as $\tilde{e}_\alpha = \{x|\mu_{\tilde{e}}(x) \geq \alpha\}$. This set is denoted as $\tilde{e}_\alpha = [\tilde{e}_\alpha^-, \tilde{e}_\alpha^+]$, where $\tilde{e}_\alpha^-$ and $\tilde{e}_\alpha^+$ are the left and right end points, respectively. Signed distance of the $\tilde{e}_\alpha^-$ of the α-level set from the origin can be obtained as:

$$\tilde{e}_\alpha^- = l(\tilde{e}) + (m(\tilde{e}) - l(\tilde{e})) \times \alpha \tag{23}$$

and the signed distance of the $\tilde{e}_\alpha^+$ from the origin can be obtained as:

$$\tilde{e}_\alpha^+ = u(\tilde{e}) - (u(\tilde{e}) - m(\tilde{e})) \times \alpha \tag{24}$$

The average of these two points is taken as the signed distance of $\tilde{e}_\alpha$ from the origin. Therefore, the signed distance of this fuzzy number ($d(\tilde{e})$) is calculated as follows:

$$d(\tilde{e}) = \int_0^1 \left[\frac{1}{2} \times (\tilde{e}_\alpha^- + \tilde{e}_\alpha^+)\right] d(\alpha) = \frac{1}{4} \times (2 \times m(\tilde{e}) + l(\tilde{e}) + u(\tilde{e})) \tag{25}$$

Thus, using the signed distance method, the fuzzy objective functions and constraint (Eqns. 19–22) are converted into crisp equations. The crisp objective function for each quantitative criterion is given in Eqns. 26–28 as follows:

$$Min\ Z_1 = \sum_{s=1}^{t} \left(\frac{l(\tilde{P}_s)+2\times m(\tilde{P}_s)+u(\tilde{P}_s)}{4}\right) \times X_s + \sum_{s=1}^{t} \left(\frac{l(\widetilde{TC}_s)+2\times m(\widetilde{TC}_s)+u(\widetilde{TC}_s)}{4}\right) \times T_s$$

$$s = 1,2, \dots . t \qquad (26)$$

$$Min\ Z_2 = \sum_{s=1}^{t} \left(\frac{l(\tilde{L}_s)+2\times m(\tilde{L}_s)+u(\tilde{L}_s)}{4}\right) \times X_s \quad s = 1,2, \dots . t \qquad (27)$$

$$Min\ Z_3 = \sum_{s=1}^{t} \left(\frac{l(\widetilde{DP}_s)+2\times m(\widetilde{DP}_s)+u(\widetilde{DP}_s)}{4}\right) \times X_s \quad s = 1,2, \dots . t \qquad (28)$$

The crisp supplier production capacity constraint can be represented as:

$$X_s \leq \left(\frac{l(\tilde{V}_s)+2\times m(\tilde{V}_s)+u(\tilde{V}_s)}{4}\right) \times Y_s \qquad s = 1,2, \dots . t \qquad (29)$$

The fourth objective function (Eq. 30) is maximising total score of suppliers (to mitigate capability-based risks). This objective function includes the scores of suppliers (U_s) obtained using COPRAS-F in Step 2 as constants which are then used with X_s for maximisation of score in FLP. By maximising the utility scores, the robustness of suppliers is increased to mitigate capability-based risks. The order requirement constraint is presented in Equation 31, where OR represents the total order requirement of the buyer company. Truck numbers, materials transported from the s^{th} supplier to company, constraint is presented in Equation 32 where p_s represents the capacity of trucks to transport material from the s^{th} supplier to the manufacturing company. Equation 33 represents the non-negative constraint for order quantity from the s^{th} supplier. Equation 34 represents Y_s as a decision variable for selecting the s^{th} supplier. The crisp objective function for the maximisation of total score and related constraints are represented as follows:

$$Max\ Z_4 = \sum_{s=1}^{t} U_s \times X_s \qquad (30)$$

$$\sum_{s=1}^{t} X_s = OR \qquad (31)$$

$$T_s = \frac{X_s}{p_s} \ (Integer) \qquad (32)$$

$$X_s \geq 0 \qquad (33)$$

$$Y_s = 0,1 \ (Binary) \tag{34}$$

$$s = 1,2, \dots . t \tag{35}$$

As the objective functions developed above constitute a set of linear programming models with fuzzy attributes, fuzzy linear programming (FLP) is used to select the most desirable suppliers and the order quantities allocated to each of those suppliers. The next subsection presents the way the weights of the objective functions are derived.

3.4.2 Comparison of Objective Functions (Step 4)

There are four objective functions (developed in Step 3) and these objective functions have different priorities. To identify priorities of objective functions, the weights of objective functions are required. FAHP is used to develop weights $(h_1, h_2, \dots, h_y)$ of objective functions. Steps of the FAHP have been presented in Section 3.3.1. In this part of the methodology, the same steps are followed to develop the weights of objective functions. The next subsection discusses the method for obtaining a solution for SES problem using the proposed FLP model.

3.4.3 Solving the Fuzzy Linear Programming Model (Step 5)

The solution process of FLP starts with the determination of the maximum and minimum values of the objective functions. Z_k presents a minimising objective function and Z_z presents a maximising objective function.

These objective functions (Z_k, Z_z) can be separated into maximum (Z_k^+, Z_z^+) and minimum (Z_k^-, Z_z^-) values to solve the multi-objective problem as a single objective problem. The maximum and minimum values of the objective functions Z_k, Z_z can be shown as:

$$Z_k^- = Min \ Z_k, \ Z_k^+ = Max \ Z_k \quad k = 1,2 \dots . N \tag{36}$$

$$Z_z^- = Min \ Z_z, \ Z_z^+ = Max \ Z_z \quad z = 1,2 \dots . \text{G} \tag{37}$$

The value of each objective (Z_k, Z_z) changes linearly from (Z_k^-, Z_z^-) to (Z_k^+, Z_z^+) and the fuzzy linear membership of the objective functions (μ_k, μ_z) are shown in Figure 3.2. N, which is the total number of minimisation of objective functions, is 3; and G, which is the total number of maximisation of objective functions, is 1 in the proposed model.

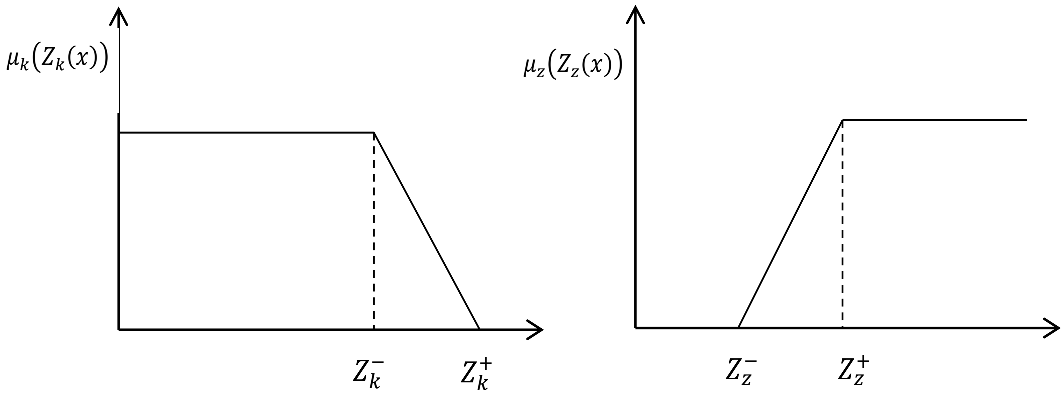

Figure 3.2: Fuzzy membership of objective functions

The linear membership functions for the objective functions (Z_k, Z_z) can be generalised mathematically as:

$$\mu_k(Z_k(x)) = \begin{cases} 1, & Z_k \leq Z_k^- \\ \frac{(Z_k^+ - Z_k(x))}{(Z_k^+ - Z_k^-)}, & Z_k^- \leq Z_k \leq Z_k^+, \; k = 1,2 \ldots .N \\ 0, & Z_k > Z_k^+ \end{cases} \tag{38}$$

$$\mu_z(Z_z(x)) = \begin{cases} 1, & Z_z \leq Z_z^+ \\ \frac{(Z_z(x) - Z_z^-)}{(Z_z^+ - Z_z^-)}, & Z_z^- \leq Z_z \leq Z_z^+, \quad z = 1,2 \ldots .\mathrm{G} \\ 0, & Z_z \leq Z_z^- \end{cases} \tag{39}$$

The maximum and minimum values of the objective functions of the FIM can be written with respect to Eqns. 36 and 37 as:

$$Z_1^- = Min\, Z_1, \; Z_1^+ = Max\, Z_1 \tag{40}$$

$$Z_2^- = Min\, Z_2, \; Z_2^+ = Max\, Z_2 \tag{41}$$

$$Z_3^- = Min\, Z_3, \; Z_3^+ = Max\, Z_3 \tag{42}$$

$$Z_4^- = Min\, Z_4,\ Z_4^+ = Max\, Z_4 \tag{43}$$

The linear membership function pertaining to the objective functions of the FIM can be computed using Eqns. 38 and 39. Z_1, Z_2 and Z_3 are the minimising objective functions, which are similar to Z_k and the linear memberships of these objective functions are calculated using Eqn. 38. For example, the linear membership of Z_1 can be shown as:

$$\mu_1\big(Z_1(x)\big) = \begin{cases} 1, & Z_1 \le Z_1^- \\ \frac{(Z_1^+ - Z_1(x))}{(Z_1^+ - Z_1^-)}, & Z_1^- \le Z_1 \le Z_1^+ \\ 0, & Z_1 > Z_1^+ \end{cases} \tag{44}$$

Z_4 is a maximising objective function, which is similar to Z_z and the linear membership of this objective function is calculated using Eqn. 39, as shown below:

$$\mu_4\big(Z_4(x)\big) = \begin{cases} 1, & Z_4 \le Z_4^+ \\ \frac{(Z_4(x) - Z_Z^-)}{(Z_4^+ - Z_4^-)}, & Z_4^- \le Z_4 \le Z_4^+ \\ 0, & Z_4 \le Z_4^- \end{cases} \tag{45}$$

After identifying the linear membership of objective functions, the single objective linear problem is solved in FLP. λ_k and λ_z represent the degrees of satisfaction for the objective functions Z_k and Z_z respectively. λ_k and λ_z can be expressed in terms of $\mu_k\big(Z_k(x)\big)$ and $\mu_z\big(Z_z(x)\big)$:

$$\lambda_k \le \mu_k\big(Z_k(x)\big) \tag{46}$$

$$\lambda_z \le \mu_z\big(Z_z(x)\big) \tag{47}$$

The weights of the objective functions were obtained in Section 3.4.2. Therefore, a single objective function (Tiwari et al., 1987) that constitutes the FLP model can be written as:

$$Max = \lambda_1 * h_1 + \lambda_2 * h_2 + \cdots + \lambda_y * h_y \tag{48}$$

Eqns. 46 and 47 can be extended through Eqns. 38 and 39 and the FLP model is solved as a single objective linear programming problem:

$$\lambda_k \leq \frac{(Z_k^+ - Z_k(x))}{(Z_k^+ - Z_k^-)} \tag{49}$$

$$\lambda_z \leq \frac{(Z_z(x) - Z_z^-)}{(Z_z^+ - Z_z^-)} \tag{50}$$

$$\lambda_k, \lambda_z \in [0,1] \tag{51}$$

$$k = 1,2 \ldots . N \tag{52}$$

$$z = 1,2 \ldots . \mathrm{G} \tag{53}$$

In Eqns. 49 and 50, supplier production capacity (Eqn. 29), order requirement constraint (Eqn. 31), truck numbers constraint (Eqn. 32), non-negative order requirement constraint (Eqn. 33) and binary constraint will be the constraints of the FLP model. With this step, the process of identifying preferred suppliers and order allocation to these suppliers are concluded.

3.5 Summary

This chapter proposed a comprehensive model (termed as a fuzzy integrated model) to mitigate capability-based and performance-based risks in the SES problem. The fuzzy integrated model (FIM) consists of five steps, which are: comparison of capability-based risks (qualitative criteria), assigning scores to suppliers, conversion of fuzzy objective functions and constraints, comparison of objective functions and solving the fuzzy linear programming model. In Step 1, FAHP is used to establish the relative importance of capability-based risks (qualitative criteria). Then, COPRAS-F is used to evaluate each supplier against capability-based risks (qualitative criteria) in Step 2. An aggregate weighted score for each supplier is obtained in this step and these scores are used as objective function coefficients in the fuzzy linear programming model, in Step 5. In Step 3, fuzzy numbers in objective functions and constraints (representing performance-based risks) are converted into crisp numbers using signed distance method. Then, the objective functions of the model are compared to establish the

relative importance of the objective functions in Step 4. In the final step, FLP is used to mitigate performance-based and capability-based risks to select preferred suppliers and allocate orders for selected suppliers. The FIM is applied to a real case study from the Turkish textile industry. The application and feasibility of the FIM based on the analysis of data from eight Turkish companies and twenty-four managers is detailed in the next chapter.

4 APPLICATION OF THE FUZZY INTEGRATED MODEL IN THE TURKISH TEXTILE INDUSTRY

4.1 Significance of the Turkish Textile Industry

The textile and apparel industry is an important part of the Turkish economy because of its contribution to gross domestic product (GDP). The Turkish textile industry has been significantly modernised since 1960s and ’70s (Cebeci, 2009). This modernisation improved the brand image for the Turkish textile and apparel industry by producing higher quality products, and Turkey has become one of the most significant textile and clothing producers and exporters in the world (Cebeci, 2009). According to Karaalp and Yilmaz (2012), textiles generated 7.1 % of total Turkish exports in 2008 and clothing products generated 10.3%. In 2008, Turkish textile exports ranked seventh and clothing exports ranked fourth among nations in the in World Trade Organisation. Karaalp and Yilmaz (2012) reported that for both textile and clothing exports, the Turkish textile industry is the second-biggest exporter to the European Union (EU) after China. Fifty-one per cent of Turkey’s textile exports and 77% of Turkey’s clothing exports were sent to the EU in 2009. Turkish textile products in particular are in demand in Germany, followed by Italy and the United Kingdom. In short, the Turkish textile industry is an important supplier for importers in the EU and worldwide. Therefore, the Turkish textile industry is used in this research for modelling and analysis in terms of mitigating risks in the supplier evaluation and selection process.

4.2 Selection of Companies

Most of the textile companies in Turkey are listed with industry associations. Therefore, companies listed on the websites of seven large industry associations in Turkey were identified through an online search. Then, 62 Turkish textile companies were identified as suitable organisations to collect data for the study, based on their

employee size and annual turnover. These textile companies, which produce garments and underwear, were classified with respect to following characteristic of companies (employee size and turnover). If company employs less than 200 staffs and its annual turnover is less than $5 million, the company was called ‘small-sized company’. These small-sized companies were not considered in this study as most of these companies supply from single supplier, which is not suitable for supplier selection. If company employs more than 200 staffs and less than 900 staffs and its annual turnover is more than $5 million and less than $15 million, the company was called ‘medium-sized company’. Some of these organisations were considered in this study, since these companies purchase items from different suppliers. However, some of medium-sized companies did not wish to participate in this study. If company employs more than 900 staff and its annual turnover is more than $15 million the company was called ‘large-sized company’. Some of these organisations were considered in this study, since these companies purchase items from different suppliers; however, some of large-sized companies did not wish to participate in this study. Contacts with Turkish textile companies were made in the following manner:

1. Purchasing managers were contacted by telephone and the purpose of this research project was explained to them. After they agreed to be the part of this project, their email addresses were obtained for further communication. Employee size (over 200 people) and turnover ($5 million) are selected for suitability characteristic of company to decide companies to participate in this study. Based on the suitability characteristic of company and the interest of companies in participating in the project, nine companies were identified out of the 62 that were contacted;

2. These nine companies were then sent an email (in Turkish) outlining the research project in detail, including the type of data/information required and the time commitments expected from participants. One company did not wish to participate in the research as the management did not consent to releasing company information; and,

3. Finally, eight companies were selected and confirmed as participants in the study.

Most previous models developed in the literature have not been validated using empirical data. Even though only managers of eight companies have participated in this study, FIM has been validated using empirical data. Before collecting data, ethics documents including questionnaires and ethics forms were prepared to obtain the approval of the university ethics committee. Ethics confirmation (see Appendix A) was obtained by 13th March 2013. The data was then collected from relevant company personnel using two semi-structured questionnaires.

The evaluation of supplier performance questionnaire (in Appendix B) was used to gather two types of data: qualitative and quantitative. The qualitative data includes linguistic variables such as ‘good’ and ‘high’. Qualitative questions were asked in Sections II, IV and V of the questionnaire (see Appendix B). This data was collected to compare capability-based risks and to rank suppliers according to these risks. The quantitative data includes fuzzy numbers, such as the most pessimistic, probabilistic and optimistic values. Quantitative questions were asked in Sections III and VI of the questionnaire (see Appendix B). This data was used to mitigate performance-based risks in the supplier selection process.

The questionnaire on the feasibility of the FIM consisted of two sections: Section I which is related to the suitability of criteria and objectives and Section II

which is related to the suitability of order allocations and the results of the model. This questionnaire is shown in Appendix C and responses w ere on an 11-point Likert scale. As 11-point Likert scale is much more granular than 5 and 7- point Likert scales, this enables decision-makers (DMs) to choose different values from extended scales. Extended scales (i.e. 11-point scale) would provide increasing variance in the measurement, therefore; unidimensional and univocal analysis can be prevented by using 11-point Likert scale (Hodge and Gillespie, 2007; Leung, 2011). Even though all Likert scales can be used as analytical tools to capture decision maker's opinion, 11-point Likert scale reduces skewness and kurtosis of data distribution to make it normal distribution (Dawes, 2008; Leung, 2011). Additionally, 11- point Likert scale increases the sensitivity of measurement without affecting reliability of measurement (Leung, 2011). Therefore, 11-point Likert scale is used to capture the opinion of managers in this study.

Six factory managers, four chief financial officers (CFOs)/financial managers, four quality managers, three purchasing managers, three planning managers, one customer relationship manager (CRM), one chief operating officer (COO), one operational director and one human resource manager (HRM) from eight selected companies participated in this research study. The numbers of managers varied from factory to factory as some managers did not agree to participate in this survey or stated that they do not to know the purchasing process. The following subsections provide brief details about the companies selected for data gathering.

4.2.1 Company A

Company A is a medium-size Turkey-based jeans and assorted garment manufacturer with over 10 years of experience in the textile industry. Annual turnover of this company exceeds $5 million. It currently employs more than 200 people and is

among the minor exporting and manufacturing corporations of Turkey. It exports shirts, t-shirts, trousers and jeans to European countries.

4.2.2 Company B

Company B is a large Turkey-based assorted garment manufacturer with over 10 years of experience in the textile industry. The company manufactures a range of textile products mainly for the Turkish market under their original brand. With an annual turnover exceeding $20 million and over 1500 staff, the company is a major manufacturer in the textile sector. It exports shirts, t-shirts, women’s and men’s clothing to Western Europe and the USA.

4.2.3 Company C

Company C is a successful medium-sized Turkey-based jeans manufacturer with over five years of experience in the textile industry. The company is a leading jeans/garment manufacturer. The annual turnover of this company is more than $5 million and the company employs over 200 staff. It manufactures women’s and men’s jeans. This company exports these products to European Union countries.

4.2.4 Company D

Company D is a leading manufacturer of woven apparels specialising in different types of woven garments, mainly trousers, jackets, dresses and overcoats. This company exports these products to European Union countries. The company has developed new fashions for over 30 years in the apparel industry. With an annual turnover exceeding $20 million and over 1300 staff, this company is a major manufacturer in the Turkish textile sector.

4.2.5 Company E

Company E is one of the world’s top quality producers of premium men’s and women’s woven shirts. It has been involved manufacturing shirts for more than 30

years. With an annual turnover exceeding $20 million and over 1200 staff, the company is a major shirt manufacturer in the textile sector.

4.2.6 Company F

Company F is a leading figure in the world of fashion, boasting over 60 years of experience in the textile sector. The company built its strategy on specialising in the design and production of shirts. Turkey's foremost producer and exporter, Company F produces over 2,000,000 shirts per year. With the opening of its production and logistics plant, which covers over 30,000 m^2 the company has joined the vanguard of shirt manufacturers. Company F manufactures shirts and t-shirts yearly for prestigious brands in Europe and the United States, with 90% of its total annual production capacity being exported. The company currently employs more than 1000 people and has an annual turnover of more than $30 million. It is one of the major exporting and manufacturing corporations of Turkey.

4.2.7 Company G

Company G is a successful medium-sized Turkey-based underwear manufacturer with over 30 years of experience in the textile industry. The company employs over 500 people. It produces various types of underwear and has an annual turnover of over $5 million. The company has three plants in different cities in Turkey. It manufactures underwear products mainly for the Turkish market under its original brand. Ten per cent of its total annual production is exported to the USA, Europe and Middle Eastern countries. The company has a great sales distribution network in Turkey.

4.2.8 Company H

Company H is a medium-sized Turkey-based shirts manufacturer with over five years of experience in the textile industry. Annual turnover of this company exceeds $5

million. The company employs over 220 staff. Even though this company is new to textile sector, it has reached Turkish quality standards. By next year, the company will commence selling its products to Middle Eastern countries.

4.3 Application of the Fuzzy Integrated Model for Supplier Selection

In this section, there are three subsections for describing the data analysis for each company. First subsection describes the application of capability-based risk assessment and performance-based risk assessment based on the proposed fuzzy integrated model (FIM). The second subsection details the results obtained after application of the FIM. Next, to measure superiority of FIM, the results of the modelling and the actual company data are compared in this subsection. In the third subsection, the model's feasibility assessment for each manager will be detailed based on the results from the feasibility questionnaire.

4.3.1 Application in Company A

In Company A, only the factory manager was interviewed to obtain data about purchasing decisions for yarn (thread spools). The interview process involved selecting the preferred supplier(s) from four possible suppliers. Other managers of Company A did not participate in this research for personal reasons. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria based on the preferences assigned by the factory manager, was carried out. Linguistic weights provided by the factory manager in evaluating qualitative criteria are shown in Table 1D in Appendix D. FAHP was used to establish the relative importance of each qualitative criterion based on the procedure described in Step 1 of Section 3.3.1 in Chapter 3. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.1.

Table 4.1: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Manager	Factory Manager
Financial Position	0.19
Volume Flexibility	0.19
Technological Capability	0.19
Reputation	0.12
Compliance with Sectoral Price	0.16
Communication Issues	0.16
CR ≤ 0.1	0.031

Based on the w_i^* of the factory manager in Table 4.1, the importance of qualitative criteria are, in order: financial position = volume flexibility = technological capability > compliance with sectoral price =communication issues> reputation.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F (Step 2 of Section 3.3.2 in Chapter 3). Linguistic scores from the factory manager for evaluating supplier performance under qualitative criteria are presented in Table 2D of Appendix D. The corresponding crisp scores (U_s) for each supplier against the qualitative criteria are shown in Table 4.2.

Table 4.2: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Manager	Factory Manager
Supplier 1	1.0000
Supplier 2	0.9991
Supplier 3	0.9593
Supplier 4	0.8254

Based on the information provided in Table 4.2, the order of preference for suppliers as indicated by the factory manager with respect to qualitative criteria is: Supplier 1>Supplier 2>Supplier 3>Supplier 4.

Fuzzy data ($\tilde{P}_s$, $\tilde{L}_s$, $\widetilde{DP}_s$, $\tilde{V}_s$) from historical survey data for 2012 are in used in the fuzzy objective functions ($\tilde{Z}_1$, $\tilde{Z}_2$, $\tilde{Z}_3$) and the constraint. This data is converted into crisp data using the signed distance method (see Step 3 of Section 3.4.1 in Chapter 3). Thus, the crisp objective functions (Z_1, Z_2, Z_3, Z_4) and a constraint were developed

followed by the computation of the weights (h_y) of the objective functions using FAHP (see Step 4 of Section 3.4.2 in Chapter 3). Linguistic values assigned by the factory manager in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 3D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.3.

Table 4.3: Weights (h_y) of the objective functions

Objective Functions \ Manager	Factory Manager
Total Cost	0.44
Late Delivery Percentage	0.24
Defect Percentage	0.24
Qualitative Aspects	0.08
CR ≤ 0.1	0.06

The crisp objective functions (Z_1, Z_2, Z_3, Z_4), together with the supplier production capacity constraint and weights (h_y) were then used in the FLP model to select preferred suppliers and to allocate orders (see Step 5 of Section 3.4.3 in Chapter 3). The degrees of satisfaction ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) for the objective functions are 1, 0.84, 1 and 0.89 respectively. Based on these results, it can be said that the proposed solution for order requirements fully satisfies the minimisation of total cost and defective unit objective functions; however, the minimisation of late delivered units and maximisation of total score are only partly satisfied (0.84 and 0.89). Even though these two objective functions are not fully satisfied by the model, the satisfaction levels of the objective functions are over 0.70. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.4.

Table 4.4: Order quantities (X_S) from the model and Company A

Suppliers	Real Order from Company A	Order Quantities using Fuzzy Integrated Model
Supplier 1	80,000	50,000
Supplier 2	50,000	90,000
Supplier 3	30,000	80,000
Supplier 4	60,000	0

As demonstrated by the results presented in Table 4.4, Supplier 4 was not selected by the FLP model. Purchasing order quantity from Supplier 1 decreases from 80,000 to 50,000. However, the purchasing order quantity from Suppliers 2 and 3 increases from 50,000 to 90,000 and from 30,000 to 80,000 respectively.

4.3.1.1 Comparison of results: Company A′s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.1 are compared with Company A's actual results for 2012. Table 4.5 provides the results of this comparison. It can be seen that if Company A's purchased order quantities were generated using the FIM, it would have been able to save \$36,635 (out of \$529,635) of the total purchasing cost and it would have been able to purchase 1,434 fewer late delivered units (out of 6,334) and 1,341 fewer defective units (out of 6,241).

Table 4.5: Savings/Improvements in the actual results for Company A

Objective Functions / Savings of Company	Cost (\$) (%)	Late Delivery Unit (%)	Defective Unit (%)
Percentage savings/improvements	6.9	22.6	21.5

Table 4.6 provides the total score (to mitigate capability-based risks) computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. This total score, represented as an objective function (Z_4) in the final FLP model, and was optimised along with other objective functions (Z_1, Z_2, Z_3) in allocating orders for the selected suppliers. The results show the difference in total score obtained using the FIM and the actual order quantities placed by the company in 2012. The total score, based on order quantities derived using the

model, is much more than the total score based on real order quantities. The robustness against capability-based risks increases with the increase in total score.

Table 4.6: Total score of suppliers for Factory Manager

Total Score \ Manager	Factory Manager
FIM's results (Order quantities)	216,663
Real order quantities (2012)	208,258

4.3.1.2 Feasibility for Company A

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, the objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the manager to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the factory manager are shown in Table 4.7.

Table 4.7: Feasibility of criteria, objectives and model

Questions \ Manager	Factory Manager
Criteria	8
Objectives	7
Suppliers	8
Results	8

The score for the feasibility of the criteria used is 8 out of 10. The score for the feasibility of the objectives used in the FIM is 7 out of 10. The feasibility score for the suppliers selected using the FIM is 8, which illustrates that the same set of suppliers that was selected using the model, could be agreed upon by the factory manager of Company A. The score for the feasibility of the results (total purchasing cost, late delivered units, and defective units) was 8. Finally, it can be concluded that factory manager rated the FIM and its results as useful (based on Table 4.7).

4.3.2 Application in Company B

In Company B, only the purchasing manager was interviewed to obtain data on purchasing decisions to select preferred supplier (s) from five suppliers to supply yarn (thread spools). Other managers of Company B did not want to participate in this research for personal reasons. The application of the model is similar to the application in case Company A, so it is not described further for other companies. Linguistic weights provided by the purchasing manager in evaluating qualitative criteria are shown in Table 4D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.8.

Table 4.8: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Manager	Purchasing Manager
Financial Position	0.34
Volume Flexibility	0.20
Technological Capability	0.14
Reputation	0.11
Compliance with Sectoral Price	0.14
Communication Issues	0.07
CR ≤ 0.1	0.057

Based on the w_i^* of the purchasing manager in Table 4.8, the importance of qualitative criteria are, in order: financial position > volume flexibility > technological capability = compliance with sectoral price> reputation >communication issues.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. The linguistic scores of the purchasing manager for evaluating supplier performance according to the qualitative criteria are indicated in Table 5D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.9.

Table 4.9: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Manager	Purchasing Manager
Supplier 1	0.9614

Supplier 2	1.0000
Supplier 3	0.8258
Supplier 4	0.7868
Supplier 5	0.9614

Based on the information provided in Table 4.9, the order of preference for suppliers as indicated by the purchasing manager with respect to qualitative criteria is: Supplier 2>Supplier 1=Supplier 5 >Supplier 3>Supplier 4.

Linguistic values assigned by purchasing manager in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 6D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.10.

Table 4.10: Weights (h_y) of the objective functions

Manager / Objective Functions	Purchasing Manager
Total Cost	0.40
Late Delivery Percentage	0.29
Defect Percentage	0.23
Qualitative Aspects	0.08
CR ≤ 0.1	0.046

The degrees of satisfaction $(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$ for each objective function are 1, 0.75, 1 and 1 respectively. As is seen, degrees of satisfaction of total cost, defective unit and total score objective functions are fully satisfied in the model. Even though minimisation of late delivered objective function is partly satisfied (0.75) by the proposed solution, the satisfaction level of this objective function is over 0.70 which can be acceptable. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.11.

Table 4.11: Order quantities (X_s) from the model and Company B

Suppliers	Real Order from Company B	Order Quantities using Fuzzy Integrated Model
Supplier 1	600,000	800,000
Supplier 2	800,000	900,000
Supplier 3	200,000	0
Supplier 4	200,000	0
Supplier 5	200,000	300,000

As demonstrated by the results presented in Table 4.11, Supplier 3 and Supplier 4 were not selected by the model. The purchasing order quantity from Supplier 1, Supplier 2 and Supplier 5 are increased by 200,000,100,000 and 100,000 respectively.

4.3.2.1 Comparison of results: Company B´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.2 are compared with Company B's actual results for 2012. Table 4.12 provides the results of this comparison. It can be seen that if Company B's purchased order quantities were generated using the FIM, it would have been able to save $118,259 (out of $ 4,568,259) of the total purchasing cost and it would have been able to purchase 1,527 (out of 41,527) fewer late delivered units and 1,823 (out of 41,823) fewer defective units.

Table 4.12: Savings/Improvements in the actual results for Company B

Objective Functions / **Savings of Company B**	**Cost ($) (%)**	**Late Delivery (Unit) (%)**	**Defective (Unit) (%)**
Percentage savings/improvements	2.5	3.7	4.4

Table 4.13 provides the total score (to mitigate capability-based risks) computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total score obtained using the FIM and the actual order quantities placed by Company B in 2012.

Table 4.13: Total score of suppliers for Purchasing Manager

Manager / **Total Score**	**Purchasing Manager**
FIM's results (Order quantities)	1,957,540
Real order quantities (2012)	1,891,640

4.3.2.2 Feasibility for Company B

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic

definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the manager to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the purchasing manager are shown in Table 4.14.

Table 4.14: Feasibility of criteria, objectives and model

Manager / **Questions**	**Purchasing Manager**
Criteria	8
Objectives	10
Suppliers	9
Results	9

The score for the feasibility of criteria used is 8 out of 10. The score for the feasibility of objectives used in the FIM is 10 out of 10, which is the highest value on the Likert scale. The feasibility score for the suppliers selected using the FIM is 9 out of 10, which illustrates that the same set of suppliers, which was selected using the model, could be agreed upon by the purchasing manager of Company B. The score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 9. Finally, it can be concluded that the purchasing manager rated the FIM and its results as useful (based on Table 4.14).

4.3.3 Application in Company C

In Company C, the factory manager, financial manager, planning manager and quality manager were interviewed to obtain data about purchasing decisions for fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the four managers, was carried out. Linguistic weights provided by the four managers in evaluating qualitative criteria are shown in

Table 7D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.15.

Table 4.15: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Factory Manager	Financial Manager	Planning Manager	Quality Manager
Financial Position	0.28	0.34	0.33	0.27
Volume Flexibility	0.23	0.22	0.22	0.22
Technological Capability	0.18	0.15	0.17	0.16
Reputation	0.15	0.14	0.10	0.13
Compliance with Sectoral Price	0.09	0.10	0.12	0.17
Communication Issues	0.07	0.06	0.06	0.06
CR ≤ 0.1	0.088	0.090	0.092	0.058

Based on the w_i^* of the factory manager in Table 4.15, the importance of the qualitative criteria are in order: financial position > volume flexibility > technological capability > reputation > compliance with sectoral price > communication issues.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 8D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.16.

Table 4.16: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Managers	Factory Manager	Financial Manager	Planning Manager	Quality Manager
Supplier 1	1.0000	0.9353	1.0000	0.9740
Supplier 2	0.7423	0.8598	0.8264	0.7590
Supplier 3	0.8812	1.0000	0.9368	0.8404
Supplier 4	0.7402	0.9251	0.8223	0.8689
Supplier 5	0.8050	0.9524	0.8580	1.0000

Based on the information provided in Table 4.16, the order of preference for suppliers as indicated by the factory manager with respect to qualitative criteria is: Supplier 1>Supplier 3>Supplier 5>Supplier 2>Supplier 4.

Linguistic values assigned by the four managers in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 9D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.17.

Table 4.17: Weights (h_y) of the objective functions

Managers / Objective Functions	Factory Manager	Financial Manager	Planning Manager	Quality Manager
Total Cost	0.45	0.40	0.42	0.38
Late Delivery Percentage	0.27	0.28	0.30	0.33
Defect Percentage	0.20	0.20	0.17	0.22
Qualitative Aspects	0.08	0.12	0.11	0.07
CR ≤ 0.1	0.064	0.075	0.070	0.091

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction $(\lambda_1, \lambda_2, \lambda_3)$ of the three objective functions for each manager are 1, 1 and 0.85 respectively. This means that the degrees of satisfaction for minimisation of the total cost and minimisation of the late delivered units is equal to 1 (fully satisfied); however, the degree of satisfaction for the minimisation of defective units is not fully satisfied (0.85). Additionally, the degree of satisfaction (λ_4) of the fourth objective function (total score) changes from manager to manager. This value for the factory manager is 0.85 and for the other managers (financial manager, planning manager, and quality manager) it is 1, 0.77 and 0.78 respectively. The degree of satisfaction for the maximisation of the total score is 1 for the financial manager; however, in case of other managers the satisfaction degrees are not fully satisfied. For example, the financial manager assigned the highest score to Supplier 3 and the order quantity for this supplier is 100,000. By comparison, the order quantities of other selected suppliers in the model are less than 100,000. The other managers (factory manager, planning manager and quality manager) assigned their highest scores to Supplier 1 and Supplier 5. The order

quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.18.

Table 4.18: Order quantities (X_s) from the model and Company C

Suppliers	Real Order from Company C	Order Quantities using Fuzzy Integrated Model
Supplier 1	100,000	70,000
Supplier 2	50,000	0
Supplier 3	25,000	100,000
Supplier 4	25,000	0
Supplier 5	50,000	80,000

As demonstrated by the results presented in Table 4.18, Suppliers 2 and 4 are not selected by the FLP model. The purchasing order quantity from Supplier 1 is decreased from 100,000 to 70,000. However, the order quantities for Supplier 3 and Supplier 5 are increased by 75,000 and 30,000 respectively.

4.3.3.1 Comparison of results: Company C´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.3 are compared with Company C’s actual results for 2012. Table 4.19 provides the results of this comparison. It can be seen that if company C’s purchased order quantities were generated using the FIM, it would have been able to save $119,622 (out of $ 989,622) of the total purchasing cost and it would have been able to purchase 1,127 (out of 6,827) fewer late delivered units and 511 (out of 5,289) fewer defective units.

Table 4.19: Savings/Improvements in the actual results for Company C

Objective Functions / Savings of Company	Cost ($) (%)	Late Delivery (Unit) (%)	Defective (Unit) (%)
Percentage savings/improvements	12.1	16.5	9.7

Table 4.20 provides the total score computed using the scores assigned to suppliers against the qualitative criteria and the order quantities allocated for these

suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.20: Total scores of suppliers for managers

Total Scores \ Managers	Factory Manager	Financial Manager	Planning Manager	Quality Manager
FIM's results (Order quantities)	222,520	241,663	232,320	232,220
Real order quantities (2012)	217,900	232,267	228,197	228,082

4.3.3.2 Feasibility for Company C

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the four managers are shown in Table 4.21.

Table 4.21: Feasibility of criteria, objectives and model

Questions \ Managers	Factory Manager	Financial Manager	Planning Manager	Quality Manager	Average
Criteria	7	8	8	7	7.5
Objectives	8	7	8	8	7.75
Suppliers	9	8	8	9	8.5
Results	9	8	8	9	8.5

The average score for the feasibility of the criteria used is 7.5 out of 10. The average score for the feasibility of objectives used in the FIM is 7.75. The average score for the feasibility of the suppliers selected using the FIM is 8.5, which illustrates that the same set of suppliers that was selected using the model, could be agreed upon by Company C. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 8.5. Finally, it can be concluded that all managers rated the FIM and its results as extremely useful (based on Table 4.21).

4.3.4 Application in Company D

In Company D, the factory manager and purchasing manager were interviewed to obtain data about purchasing decisions for fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the two managers was carried out. Linguistic weights provided by the two managers in evaluating the qualitative criteria are shown in Table 10D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.22.

Table 4.22: The normalised weights (w_i^*) of qualitative criteria

Managers / Criteria	Factory Manager	Purchasing Manager
Financial Position	0.26	0.22
Volume Flexibility	0.22	0.23
Technological Capability	0.15	0.13
Reputation	0.15	0.14
Compliance with Sectoral Price	0.15	0.15
Communication Issues	0.09	0.13
CR ≤ 0.1	0.045	0.071

Based on the w_i^* of the factory manager in Table 4.22, the importance of qualitative criteria are, in order: financial position > volume flexibility > technological capability = reputation = compliance with sectoral price > communication issues.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 11D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.23.

Table 4.23: Scores of suppliers (U_s) under qualitative criteria

Managers / Suppliers	Factory Manager	Purchasing Manager
Supplier 1	1.0000	0.9870
Supplier 2	0.9438	0.9103
Supplier 3	0.9477	0.9536

Supplier 4	0.9477	0.9568
Supplier 5	0.9722	1.0000
Supplier 6	0.8049	0.8923
Supplier 7	0.7654	0.8131

Based on the information provided in Table 4.23, the order of preference for suppliers as indicated by the factory manager with respect to qualitative criteria is: Supplier 1>Supplier 5>Supplier 3=Supplier 4>Supplier 2>Supplier 6> Supplier 7.

Linguistic values assigned by the two managers in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 12D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.24.

Table 4.24: Weights (h_y) of the objective functions

Objective Functions \ Managers	Factory Manager	Purchasing Manager
Total Cost	0.46	0.38
Late Delivery Percentage	0.25	0.28
Defect Percentage	0.18	0.23
Qualitative Aspects	0.11	0.11
CR ≤ 0.1	0.061	0.091

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction $(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$ for the four objective functions for each manager are 1, 0.84, 0.98 and 1 respectively. The degrees of satisfaction for minimisation of the total cost and maximisation of the total score objective functions equals 1 and for the minimisation of defective unit is nearly fully satisfied (0.98). The minimisation of the late delivered unit objective function has the satisfaction degree of 0.84. The underlying reason for this is that the late delivered percentage of Supplier 4 is higher than the late delivered percentage of Supplier 2. Both Supplier 2 and Supplier 4, are selected by the model, however, the allocated order quantity of Supplier 2 is significantly less than its capacity and the allocated order quantity of Supplier 4 is

nearly equal to its capacity. There is a trade-off between the degree of satisfaction for minimisation of the delivered unit and minimisation of the total cost objective function. This means the satisfaction decrees for both objective functions cannot be satisfied fully. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.25.

Table 4.25: Order quantities (X_s) from the model and Company D

Suppliers	Real Order from Company D	Order Quantities using Fuzzy Integrated Model
Supplier 1	1,050,000	1,200,000
Supplier 2	700,000	450,000
Supplier 3	350,000	500,000
Supplier 4	350,000	500,000
Supplier 5	700,000	850,000
Supplier 6	175,000	0
Supplier 7	175,000	0

As demonstrated by the results presented in Table 4.25, Suppliers 6 and 7 are not selected by the FLP model. Purchasing order quantity from Supplier 2 decreased from 700,000 to 450,000. The order quantity for Supplier 1, Supplier 3, Supplier 4, and Supplier 5 all increased by 150,000.

4.3.4.1 Comparison of results: Company D´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.4 are compared with Company D's actual results for 2012. Table 4.26 provides the results of this comparison. It can be see that if Company D's purchased order quantities were generated using the FIM, it would have been able to save $487,926 (out of $13,487,926) of the total purchasing cost and would have been able to purchase 13,234 (out of 438,234) fewer late delivered units and 7,605 (out of 92,105) fewer defective units.

Table 4.26: Savings/Improvements in the actual results for Company D

Objective Functions / Savings of Company	Cost ($) (%)	Late Delivery Unit (%)	Defective Unit (%)
Percentage savings/improvements	3.6	3	8.2

Table 4.27 provides the total score computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.27: Total scores of suppliers for managers

Managers / Total Scores	Factory Manager	Purchasing Manager
FIM's results (Order quantities)	3,398,780	3,399,235
Real order quantities (2012)	3,329,392	3,340,645

4.3.4.2 Feasibility for Company D

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the two managers are shown in Table 4.28.

Table 4.28: Feasibility of criteria, objectives and model

Managers / Questions	Factory Manager	Purchasing Manager	Average
Criteria	8	7	7.5
Objectives	9	9	9
Suppliers	9	8	8.5
Results	9	8	8.5

The average feasibility score for the feasibility of criteria used is 7.5 out of 10. The average feasibility score for the feasibility of objectives used in the FIM is 9. The average feasibility score for the suppliers selected using the FIM is 8.5, which illustrates

that the same set of suppliers, which was selected using the model, could be agreed upon by Company D. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 8.5. Finally, it can be concluded that all managers rated the FIM and its results as extremely useful (based on Table 4.28).

4.3.5 Application in Company E

In company E, the operational director, the chief financial officer (CFO); the planning manager; and the chief operating officer (COO) were interviewed to obtain data on purchasing decisions about fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the four managers, was carried out. Linguistic weights provided by the four managers in evaluating qualitative criteria are shown in Table 13D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.29.

Table 4.29: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Operational Director	CFO	COO	Planning Manager
Financial Position	0.26	0.16	0.20	0.31
Volume Flexibility	0.20	0.19	0.17	0.20
Technological Capability	0.14	0.19	0.15	0.20
Reputation	0.11	0.16	0.17	0.13
Compliance with Sectoral Price	0.15	0.14	0.15	0.07
Communication Issues	0.14	0.16	0.16	0.09
CR ≤ 0.1	0.080	0.043	0.085	0.069

Based on the w_i^* of the operational director in Table 4.29, the importance of qualitative criteria are, in the order: financial position> volume flexibility> compliance with sectoral price>technological capability = communication issues>reputation.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 14D of Appendix D. The

corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.30.

Table 4.30: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Managers	Operational Director	CFO	COO	Planning Manager
Supplier 1	1.0000	1.0000	1.0000	1.0000
Supplier 2	0.9450	0.9265	0.8933	0.9435
Supplier 3	0.9122	0.8808	0.8933	0.8999
Supplier 4	0.8067	0.7611	0.7001	0.8039
Supplier 5	0.9072	0.8719	0.8453	0.8967
Supplier 6	0.9588	0.9632	0.9442	0.9707
Supplier 7	0.8698	0.8262	0.8367	0.8438

Based on the information provided in Table 4.30, the order of preference for suppliers as indicated by the operational director with respect to qualitative criteria is: Supplier 1>Supplier 6>Supplier 2>Supplier 3>Supplier 5>Supplier 7> Supplier 4.

Linguistic values assigned by the four managers in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 15D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.31.

Table 4.31: Weights (h_y) of the objective functions

Objective Functions \ Managers	Operational Director	CFO	COO	Planning Manager
Total Cost	0.37	0.39	0.34	0.34
Late Delivery Percentage	0.30	0.29	0.34	0.38
Defect Percentage	0.24	0.20	0.20	0.21
Qualitative Aspects	0.09	0.12	0.12	0.07
CR ≤ 0.1	0.061	0.052	0.055	0.086

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) of each objective function for each manager were taken as one (the highest satisfaction value). The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.32.

Table 4.32: Order quantities (X_S) from the model and Company E

Suppliers	Real Order from Company E	Order Quantities using Fuzzy Integrated Model
Supplier 1	1,500,000	1,500,000
Supplier 2	1,000,000	1,000,000
Supplier 3	1,000,000	1,000,000
Supplier 4	600,000	0
Supplier 5	400,000	800,000
Supplier 6	300,000	300,000
Supplier 7	200,000	400,000

As demonstrated by the results presented in Table 4.32, Supplier 4 was not selected by the FLP model. Purchasing order quantity from Supplier 1, Supplier 2, Supplier 3 and Supplier 6 are the same as those actually ordered by Company E. The purchasing order quantity for Supplier 5 has increased from 400,000 to 800,000 and Supplier 7's order quantity has increased from 200,000 to 400,000. This is reflected in the order quantity of Supplier 4 being shared between Supplier 5 and Supplier 7. Even though the allocated order quantity for each supplier changes slightly, these changes have significant effects on purchasing cost, late delivered units and defective units.

4.3.5.1 Comparison of results: Company E´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.5 are compared with Company E's actual results for 2012. Table 4.33 provides the results of this comparison. It can be seen that if Company E's purchased order quantities were generated using the FIM, it would have been able to save $600,000 (out of $27,200,000) of the total purchasing cost and it would have been able to purchase 60,000 (out of 1,165,000) fewer late delivered units and 4,000 (out of 196,000) fewer defective units.

Table 4.33: Savings/Improvements in the actual results for Company E

Objective Functions / Savings of Company	Cost ($) (%)	Late Delivery Unit) (%)	Defective Unit (%)
Percentage savings/improvements	2.2	5.2	2

Table 4.34 provides the total score computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.34: Total scores of suppliers for managers

Managers / Total Scores	Operational Director	CFO	COO	Planning Manager
FIM's results (Order quantities)	4,718,520	4,624,260	4,580,780	4,689,490
Real order quantities (2012)	4,665,700	4,566,920	4,495,380	4,644,390

4.3.5.2 Feasibility for Company E

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the four managers are shown in Table 4.35.

Table 4.35: Feasibility of criteria, objectives and model

Managers / Questions	Operational Director	CFO	COO	Planning Director	Average
Criteria	8	8	9	8	8.25
Objectives	10	10	9	10	9.75
Suppliers	9	9	8	8	8.5
Results	9	9	8	8	8.5

The average feasibility score for the feasibility of criteria used is 8.25 out of 10. All the managers rated objectives used in the FIM to be highly useful and completely feasible by assigning an average score of 9.75. The feasibility score for the suppliers

selected using the FIM was 8.5, which illustrates that the same set of suppliers which was selected using the model, could be agreed upon by Company E. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 8.5. Finally, it can be concluded that all managers rated the FIM and its results as extremely useful (based on Table 4.35).

4.3.6 Application in Company F

In Company F, the factory manager, planning manager, quality manager, purchasing manager, human resource manager (HRM), and customer relationship manager (CRM) were interviewed to obtain data on purchasing decisions about fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the six managers was carried out. Linguistic weights provided by the six managers in evaluating the qualitative criteria are shown in Table 16D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.36.

Table 4.36: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Factory Manager	Planning Manager	Quality Manager	Purchasing Manager	HRM	CRM
Financial Position	0.18	0.23	0.31	0.26	0.28	0.21
Volume Flexibility	0.15	0.18	0.17	0.20	0.24	0.16
Technological Capability	0.18	0.25	0.16	0.16	0.16	0.14
Reputation	0.18	0.13	0.12	0.13	0.11	0.16
Compliance with Sectoral Price	0.14	0.09	0.10	0.10	0.08	0.16
Communication Issues	0.16	0.12	0.14	0.15	0.13	0.16
CR ≤ 0.1	0.061	0.052	0.092	0.078	0.084	0.029

Based on the w_i^* of the factory manager in Table 4.36, the importance of qualitative criteria are, in order: financial position = technological capability = reputation > communication issues > volume flexibility> compliance with sectoral price.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 17D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.37.

Table 4.37: Scores of suppliers (U_s) under qualitative criteria

Managers / Suppliers	Factory Manager	Planning Manager	Quality Manager	Purchasing Manager	HRM	CRM
Supplier 1	0.9520	1.0000	0.9487	1.0000	1.0000	0.8986
Supplier 2	0.7662	0.8580	0.9460	0.8345	0.8886	0.7809
Supplier 3	0.7332	0.8580	0.9026	0.7981	0.9107	0.7809
Supplier 4	0.7332	0.8126	0.8447	0.8591	0.8905	0.8070
Supplier 5	0.8877	0.9589	0.9662	0.9581	0.9922	1.0000
Supplier 6	1.0000	0.9589	1.0000	0.9957	0.9922	0.9439
Supplier 7	0.8978	0.9589	0.9921	0.9107	0.9922	0.8661

Based on the information provided in Table 4.37, the order of preference for suppliers as indicated by the factory manager with respect to qualitative criteria is Supplier 6>Supplier 1>Supplier 7>Supplier 5>Supplier 2>Supplier 3= Supplier 4.

Linguistic values assigned by the six managers in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 18D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.38.

Table 4.38: Weights (h_y) of the objective functions

Managers / Objective Functions	Factory Manager	Planning Manager	Quality Manager	Purchasing Manager	HRM	CRM
Total Cost	0.36	0.39	0.37	0.34	0.36	0.33
Late Delivery Percentage	0.26	0.30	0.30	0.29	0.29	0.28
Defect Percentage	0.24	0.19	0.24	0.27	0.21	0.25
Qualitative Aspects	0.14	0.12	0.09	0.10	0.14	0.14
CR ≤ 0.1	0.098	0.046	0.061	0.052	0.069	0.060

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are

the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction ($\lambda_1, \lambda_2, \lambda_3$) of three objective functions for each manager are 1, 1 (the highest satisfaction value) and 0.85 respectively. As is seen, the degrees of satisfaction for minimisation of the total cost and minimisation of the late delivered unit objective function are fully satisfied by the model; however, the degree of satisfaction for minimisation of the defective unit objective function (0.85) is not fully satisfied. The degree of satisfaction (λ_4) of the fourth objective function (maximisation of the total score) changes from manager to manager. For example, this value for the planning manager, purchasing manager, human resource manager (HRM) and customer relationship manager (CRM) is 1 and for the other managers (factory manager and quality manager) it is 0.98 and 0.87 respectively. The degree of satisfaction for maximisation of total score is fully satisfied for planning manager, purchasing manager, HRM and CRM; however, the degrees of satisfaction for this objective function for other managers (factory manager and quality manager) are not fully satisfied (0.98 and 0.87) as they assigned different scores to different suppliers. For example, the factory manager and quality manager assigned the highest score to Supplier 6 and the order quantity for this supplier is 700,000. By comparison, the other managers (planning manager, purchasing manager and HRM) assigned their highest scores to Supplier 1 and the order quantity for this supplier is 1,500,000 (the highest order quantity). Even though the CRM assigned the highest score to Supplier 5, the degree of satisfaction for maximisation of the total score objective function is 1. This is due to the fact that the CRM assigned high scores to Suppliers 5, 6 and 1, and the total order quantity purchased from these suppliers is 2,900,000. However, the factory manager and quality manager assigned high scores to Suppliers 1, 6, 7 and Suppliers 5, 6, 7 respectively, and total order quantity purchased from Suppliers 1, 6, 7 is 2,300,000 and Suppliers 5, 6, 7

1,500,000. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.39.

Table 4.39: Order quantities (X_s) from the model and Company F

Suppliers	Real Order from Company F	Order Quantities using Fuzzy Integrated Model
Supplier 1	1,500,000	1,500,000
Supplier 2	600,000	0
Supplier 3	200,000	0
Supplier 4	100,000	0
Supplier 5	200,000	700,000
Supplier 6	300,000	700,000
Supplier 7	100,000	100,000

As demonstrated by the results presented in Table 4.39, Supplier 2, Supplier 3 and Supplier 4 are not selected by the FLP model. Purchasing order quantity from Supplier 1 and Supplier 7 remained at values similar to the real order quantities. The purchasing order quantity for Supplier 5 increased from 200,000 to 700,000 and Supplier 6's order quantity increased from 300,000 to 700,000.

4.3.6.1 Comparison of results: Company F´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.6 are compared with Company F's actual results for 2012. Table 4.40 provides the results of this comparison. It can be seen that if Company F's purchased order quantities were generated using the FIM, it would have been able to save $962,202 (out of $12,987,952) of the total purchasing cost and it would have been able to purchase 18,823 (out of 169,823) fewer late delivered units and 8,214 (out of 68,214) fewer defective units.

Table 4.40: Savings/Improvements in the actual results for Company F

Objective Functions / Savings of Company	Cost ($) (%)	Late Delivery Unit) (%)	Defective Unit (%)
Percentage savings/improvements	7.4	11	12

Table 4.41 provides the total score computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.41: Total scores of suppliers for managers

Managers / Total Scores	Factory Manager	Planning Manager	Quality Manager	Purchase Manager	HRM	CRM
FIM's results (Order quantities)	2,839,170	2,938,350	2,898,600	2,958,730	2,988,300	2,795,240
Real order quantities (2012)	2,675,000	2,843,000	2,848,090	2,827,630	2,899,670	2,623,100

4.3.6.2 Feasibility for Company F

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the six managers are shown in Table 4.42.

Table 4.42: Feasibility of criteria, objectives and model

Managers / Questions	Factory Manager	Planning Manager	Quality Manager	Purchase Manager	HRM	CRM	Average
Criteria	9	9	9	9	9	9	9
Objectives	8	9	9	10	10	9	9.2
Suppliers	9	10	9	8	9	8	8.8
Results	9	9	9	10	10	8	9.2

The average score for the feasibility of criteria used is 9 out of 10. All the managers have rated the objectives used in the FIM to be highly useful and completely feasible by assigning an average score of 9.2. The feasibility score for the suppliers selected using the FIM was 8.8, which illustrates that the same set of suppliers that was selected using the model, could be agreed upon by Company F. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 9.2. Finally, it can be concluded that all managers rated the FIM and its results as extremely useful (based on Table 4.42).

4.3.7 Application in Company G

In Company G, the factory manager, financial manager and quality manager were interviewed to obtain data on purchasing decisions about fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the three managers was carried out. Linguistic weights provided by the three managers in evaluating qualitative criteria are shown in Table 19D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.43.

Table 4.43: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Factory Manager	Financial Manager	Quality Manager
Financial Position	0.26	0.31	0.16
Volume Flexibility	0.20	0.21	0.21
Technological Capability	0.14	0.15	0.14
Reputation	0.11	0.09	0.16
Compliance with Sectoral Price	0.15	0.12	0.16
Communication Issues	0.15	0.13	0.16
CR ≤ 0.1	0.096	0.08	0.044

Based on the w_i^* of the factory manager in Table 4.43, the importance of qualitative criteria are, in order: financial position > volume flexibility > compliance with sectoral price = communication issues > technological capability > reputation.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 20D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.44.

Table 4.44: Scores of suppliers (U_s) under qualitative criteria

Managers / Suppliers	Factory Manager	Financial Manager	Quality Manager
Supplier 1	0.8734	0.9062	0.9291
Supplier 2	0.9715	0.8801	0.8782
Supplier 3	1.0000	1.0000	1.0000

Based on the information provided in Table 4.44, the order of preference for suppliers as indicated by factory manager with respect to qualitative criteria is: Supplier 3>Supplier 2>Supplier 1.

The calculation of order allocation is a bit different for this company, as this company considers transportation costs in order allocation. Therefore, Equation 32 (see Step 3 of Section 3.4.1 in Chapter 3) takes into account the order allocation (see Step 5 of Section 3.4.3 in Chapter 3). Linguistic values assigned by the three managers in identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 21D of Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.45.

Table 4.45: Weights (h_y) of the objective functions

Managers / Objective Functions	Factory Manager	Financial Manager	Quality Manager
Total Cost	0.37	0.38	0.46
Late Delivery Percentage	0.30	0.20	0.25
Defect Percentage	0.24	0.25	0.18
Qualitative Aspects	0.09	0.17	0.11
CR ≤ 0.1	0.061	0.039	0.061

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction ($\lambda_1, \lambda_2, \lambda_3$) of the three objective functions for each manager are all 1 (the highest satisfaction value). However, the degree of satisfaction (λ_4) of the fourth objective function changes from one manager to the other. For example, this value for the factory manager is 1 and for the financial manager and quality manager it is 0.95 and 0.91 respectively. The degree of satisfaction for the maximisation of the total score objective function for all managers shows they are fully satisfied or nearly fully satisfied (>0.90) and this means that the model has satisfied all objectives of Company G. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.46.

Table 4.46: Order quantities (X_s) from the model and Company G

Suppliers	Real Order from Company G	Order Quantities using Fuzzy Integrated Model
Supplier 1	200,000	0
Supplier 2	200,000	100,000
Supplier 3	200,000	500,000

As demonstrated by the results presented in Table 4.46, Supplier 1 was not selected by the FLP model. The purchasing order quantity for Supplier 2 is decreased from 200,000 to 100,000. The order quantity of Supplier 3 is increased from 200,000 to 500,000. As is seen, the order quantity of Supplier 1 is provided from Supplier 3.

4.3.7.1 Comparison of results: Company G′s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defective percentages for order quantities obtained in Section 4.3.7 are compared with Company G's actual results for 2012. Table 4.47 provides the results of this comparison. It can be seen that if Company

G's purchased order quantities were generated using the FIM, it would have been able to save $159,422 (out of $1,759,822) of the total purchasing cost and would have been able to purchase 45,689 (out of 115,689) fewer late delivered units and 3,289 (out of 21,289) fewer defective units.

Table 4.47: Savings/Improvements in the actual results for Company G

Objective Functions / Savings of Company	Cost ($) (%)	Late Delivery Unit (%)	Defective Unit (%)
Percentage savings/improvements	9	39.5	15.4

Table 4.48 provides the total scores computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.48: Total scores of suppliers for managers

Managers / Total Scores	Factory Manager	Financial Manager	Quality Manager
FIM's results (Order quantities)	597,150	588,010	587,820
Real order quantities (2012)	568,980	557,260	561,460

4.3.7.2 Feasibility for Company G

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the three managers are shown in Table 4.49.

Table 4.49: Feasibility of criteria, objectives and model

Managers / Questions	Factory Manager	Financial Manager	Quality Manager	Average
Criteria	9	8	9	8.7
Objectives	7	8	9	8
Suppliers	9	9	9	9
Results	8	9	9	8.7

The average feasibility score for the feasibility of criteria used is 8.7 out of 10. All the managers rated the objectives used in the FIM to be highly useful and completely feasible by assigning an average score of 8. The feasibility score for the suppliers selected using the FIM was 9, which illustrates that the same set of suppliers, which was selected using the model, could be agreed upon by Company G. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 8.7. Finally, it can be concluded that all managers rated the FIM and its results as extremely useful (based on Table 4.49).

4.3.8 Application in Company H

In Company H, the factory manager, financial manager and quality manager were interviewed to obtain data on purchasing decisions about fabric (per metre) for analysis of the supplier selection process. First, the treatment of qualitative attributes, including the evaluation of suppliers against qualitative criteria, based on the preferences assigned by the three managers was carried out. Linguistic weights provided by the three managers in evaluating qualitative criteria are shown in Table 22D in Appendix D. The resulting normalised weights (w_i^*) of the qualitative criteria are shown in Table 4.50.

Table 4.50: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Factory Manager	Financial Manager	Quality Manager
Financial Position	0.29	0.30	0.28
Volume Flexibility	0.22	0.25	0.22
Technological Capability	0.16	0.17	0.17
Reputation	0.14	0.10	0.14
Compliance with Sectoral Price	0.07	0.11	0.11
Communication Issues	0.12	0.07	0.08
$CR \leq 0.1$	0.083	0.076	0.094

Based on the w_i^* of the factory manager in Table 4.50, the importance of qualitative criteria are, in order: financial position> volume flexibility> technological capability> reputation> communication issues> compliance with sectoral price.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of managers for evaluating supplier performance under qualitative criteria are indicated in Table 23D of Appendix D. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 4.51.

Table 4.51: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Managers	Factory Manager	Financial Manager	Quality Manager
Supplier 1	1.0000	1.0000	1.0000
Supplier 2	0.8683	0.9497	0.9531
Supplier 3	0.7989	0.7715	0.8115
Supplier 4	0.9250	0.9110	0.9854

Based on the information provided in Table 4.51, the order of preference for suppliers as indicated by factory manager with respect to qualitative criteria is Supplier 1>Supplier 4>Supplier 2>Supplier 3.

The calculation of order allocation is a bit different for this company, as this company considers transportation cost in order allocation. Therefore, Equation 32 (see Step 3 of Section 3.4.1 in Chapter 3) takes into account in the order allocation (see Step 5 of Section 3.4.3 in Chapter 3). Linguistic values assigned by the three managers in

identifying h_y of the objective functions (Z_1, Z_2, Z_3, Z_4) are provided in Table 24D of the Appendix D. The crisp weights (h_y) of the objective functions are given in Table 4.52.

Table 4.52: Weights (h_y) of the objective functions

Objective Functions \ Managers	Factory Manager	Financial Manager	Quality Manager
Total Cost	0.47	0.46	0.45
Late Delivery Percentage	0.21	0.25	0.24
Defect Percentage	0.21	0.18	0.20
Qualitative Aspects	0.11	0.11	0.10
CR ≤ 0.1	0.035	0.061	0.055

Even though different weights (h_y) of objective functions (Z_1, Z_2, Z_3, Z_4) were used in the FLP model, selected suppliers and allocated orders for these suppliers are the same for each manager. This confirms the internal validity of the FIM. The degrees of satisfaction $(\lambda_1, \lambda_2, \lambda_3)$ of three objective functions for each manager are 1, 0.91, 0.78 respectively. The degree of satisfaction (λ_4) of the fourth objective function changes from manager to manager. For example, this value for the factory manager is 0.88 and for the other managers (financial manager and quality manager) it is 1 and 0.90 respectively. The order quantities obtained using the FIM and the actual quantities ordered in 2012 are provided in Table 4.53.

Table 4.53: Order quantities (X_s) from the model and Company H

Suppliers	Real Order from Company H	Order Quantities using Fuzzy Integrated Model
Supplier 1	600,000	700,000
Supplier 2	100,000	200,000
Supplier 3	200,000	0
Supplier 4	100,000	100,000

As demonstrated by the results presented in Table 4.53, Supplier 3 was not selected by the FLP model. Purchasing order quantity from Supplier 4 is the same as those actually ordered by Company H. The order quantities of Supplier 1 and Supplier 2 were increased by 100,000.

4.3.8.1 Comparison of results: Company H´s actual results vs. the results generated using fuzzy integrated model

The values for cost, late delivery percentage, and defect percentages for order quantities obtained in Section 4.3.8 are compared with Company H's actual results for 2012. Table 4.54 provides the results of this comparison. It can be seen that if company H's purchased order quantities were generated using the FIM, it would have been able to save $160,628 (out of $ 5,396,528) of the total purchasing cost and it would have been able to purchase 13,547 (out of 113,547) fewer late delivered units and 2,927 (out of 25,927) fewer defective units.

Table 4.54: Savings/Improvements in the actual results for Company H

Objective Functions / **Savings of Company**	**Cost ($) (%)**	**Late Delivery Unit (%)**	**Defective Unit (%)**
Percentage savings/improvements	2.9	11.9	11.2

Table 4.55 provides the total score computed using the scores assigned to suppliers against qualitative criteria and the order quantities allocated for these suppliers. The results show the difference in total scores obtained using the FIM and the actual order quantities placed by the company in 2012.

Table 4.55: Total scores of suppliers for managers

Managers / **Total Score**	**Factory Manager**	**Financial Manager**	**Quality Manager**
FIM's results (Order quantities)	966,160	981,040	989,160
Real order quantities (2012)	939,110	940,370	956,150

4.3.8.2 Feasibility for Company H

An 11-point Likert scale was used to assess the feasibility of the evaluation criteria, objectives and the FIM used. Three numbers in the scale have linguistic definitions, which are 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Four questions were asked of the managers to determine the feasibility of the

selection criteria, the objectives used, the suppliers selected and the results of the FIM. The feasibility scores assigned by the three managers are shown in Table 4.56.

Table 4.56: Feasibility of criteria, objectives and model

Managers / Questions	Factory Manager	Financial Manager	Quality Manager	Average
Criteria	9	9	9	9
Objectives	9	8	8	8.3
Suppliers	8	8	8	8
Results	8	8	8	8

The average feasibility score for the feasibility of criteria used is 9 out of 10. All the managers rated the objectives used in the FIM to be highly useful and completely feasible by assigning an average score of 8.3. The feasibility score for the suppliers selected using the FIM was 8, which illustrates that the same set of suppliers that was selected using the model, could be agreed upon by Company H. The average score for the feasibility of results (total purchasing cost, late delivered units, and defective units) was 8. Finally, it can be concluded that all managers rated the FIM and its results as useful (based on Table 4.56). Next subsection will compare the FIM and an integrated model to test effectiveness of the FIM.

4.4 Comparative Analysis

In this subsection, the FIM is compared with an integrated model, which is called possibilistic integrated model (PIM) in this thesis, including FAHP, FTOPSIS (Zeydan et al., 2011) and possibilistic linear programming (PLP) (Özgen et al., 2008) to test the effectiveness of the FIM. Özgen et al. (2008) proposed AHP and PLP to solve a SES problem. However, AHP is not sufficient to handle fuzzy values and to analyse both beneficial and non-beneficial criteria together. Therefore, FAHP is used to handle fuzzy values and FTOPSIS is used to analyse both beneficial and non-beneficial criteria together in the PIM. The FIM and the PIM are used to solve SES problem for only one company (i.e. Company D). The weights of criteria and objective functions of managers

of Company D will not change for this integrated model as the using of FAHP is same for the FIM and the PIM. Therefore, the results of FTOPSIS and COPRAS-F will be compared to test the effectiveness of COPRAS-F. The results of the FTOPSIS and the COPRAS-F are indicated for managers of Company D in Table 4.57.

Table 4.57: The Results of FTOPSIS and COPRAS-F

Managers / Suppliers	Factory Manager FTOPSIS used	Factory Manager COPRAS-F used	Purchase Manager FTOPSIS Used	Purchase Manager COPRAS-F used
Supplier 1	0.1717	1.0000	0.2260	0.9870
Supplier 2	0.1650	0.9438	0.1721	0.9103
Supplier 3	0.1643	0.9477	0.1765	0.9536
Supplier 4	0.1643	0.9477	0.1781	0.9568
Supplier 5	0.1679	0.9722	0.1826	1.0000
Supplier 6	0.1472	0.8049	0.1722	0.8923
Supplier 7	0.1421	0.7654	0.1610	0.8131

The order of preference for suppliers for factory manager calculated by FTOPSIS and COPRAS-F did not change; however, the order of preference for suppliers for purchase manager of FTOPSIS and COPRAS-F changed. The order of suppliers for purchase manager calculated by FTOPSIS is: Supplier 1> Supplier 5>Supplier 4> Supplier 3> Supplier 6> Supplier 2> Supplier 7. The order of suppliers for purchase manager calculated by COPRAS-F is: Supplier 5> Supplier 1>Supplier 4> Supplier 3> Supplier 2> Supplier 6> Supplier 7. FTOPSIS reached inferior results as fuzzy values assigned by purchase manager to Supplier 5 are highest values. Therefore, Supplier 5 should be the best supplier. Additionally, the performance of Supplier 6 should not be higher than that of Supplier 2 as fuzzy values of Supplier 6 are not higher than Supplier 2. It can be said that the performance of COPRAS-F is better than FTOPSIS. The scores obtained by FTOPSIS are used in PLP as the weights of the objective functions. The order allocation for PLP and FLP are indicated Company D in Table 4.58.

Table 4.58: The Order Allocation for PLP and FLP

Methods / Suppliers	Possibilistic Linear Programming	Fuzzy Linear Programming
Supplier 1	1,100,000	1,200,000
Supplier 2	688,333	450,000
Supplier 3	400,000	500,000
Supplier 4	510,000	500,000
Supplier 5	756,667	850,000
Supplier 6	45,000	0
Supplier 7	0	0

The results of PLP are $13,112,500 cost, 425,500 late delivered units and 86,883 defective units. The results of FLP are $13,000,000 cost, 425,000 late delivered units and 84,500 defective units. It can be seen that if PLP were used to solve SES problem for Company D, it would have been able to renounce $112,500 (out of $ 13,000,000) of the total purchasing cost and it would have been able to purchase 500(out of 425,000) more late delivered units and 2,383 (out of 84,500) more defective units. It can be said that the FIM, which was used to solve SES problem in this thesis, is more effective than the PIM.

4.5 Summary

Table 4.59 below shows the participant managers and their companies, and the total number of participant managers. According to Table 4.59, the number of managers is twenty-four and this number changed from company to company due to the accessibility of managers or their high-level positions in their company. An 'X' in Table 4.59 indicates inaccessibility or unavailability of managers. The FIM obtained the highest saving with respect to cost in analysing data from Company C, which was a saving 11.9 % of costs. The FIM obtained the lowest saving with respect to costs in analysing data of Company B, which was 2.4 %. The FIM obtained the highest improvement concerning late delivery percentage in analysing the data of Company G, which was an improvement of 30%. The FIM obtained the highest improvement with regards to defective percentage in analysing the data from Company A, with a reduction

of 23.4 %. All managers interviewed accepted that the FIM is feasible for textile industry. It is clear that none of them assigned the model less than 7 (out of 10) in Question 4 in the feasibility questionnaire (see Appendix B).

Table 4.59: Managers and their companies

Managers / **Companies**	**Factory Manager/ Operational Director**	**CFO/ Financial Manager**	**Planning Manager**	**Quality Manager**	**Purchase Manager**	**COO**	**HRM**	**CRM**
Company A	1	X	X	X	X	X	X	X
Company B	X	X	X	X	1	X	X	X
Company C	1	1	1	1	X	X	X	X
Company D	1	X	X	X	1	X	X	X
Company E	1	1	1	X	X	1	X	X
Company F	1	X	1	1	1	X	1	1
Company G	1	1	X	1	X	X	X	X
Company H	1	1	X	1	X	X	X	X
TOTAL	7	4	3	4	3	1	1	1

5 DEVELOPMENT AND VERIFICATION OF THE FUZZY STOCHASTIC INTEGRATED MODEL

5.1 Introduction

This chapter proposes an extended version of the fuzzy integrated model (FIM) described in Chapter 3. In FIM, a fuzzy analytic hierarchy process (FAHP), fuzzy complex proportional assessment (COPRAS-F) and fuzzy linear programming (FLP) were used to mitigate performance-based and capability-based risks for *a single item in a time period* to solve supplier evaluation and selection (SES) problem. FIM was finally validated by its application to eight Turkish textile companies and the results were described in Chapter 4. In contrast, the modelling method discussed in this chapter deals with single/multiple item(s) and multiple time periods to solve stochastic the SES problem. This formulation is realistic as the SES in real world seldom focuses on a single item and single time period and real world datasets are largely stochastic (defined by data distributions) rather than involving a predetermined number. The method described in this chapter is named as the fuzzy stochastic integrated model (FSIM). The proposed approach employs fuzzy AHP, COPRAS-F and fuzzy stochastic goal programming (FSGP) to mitigate performance-based and capability-based risks for scenarios with multiple items and multiple time periods. This model uses numerical stochastic datasets. The main extensions of the FSIM, compared the FIM of Chapter 3, are:

1. In FIM, only qualitative and fuzzy quantitative data can be considered for the SES problem. The FSIM can take into account qualitative, fuzzy and stochastic quantitative data. The inclusion of stochastic data into the FSIM provides more robust and effective solutions than fuzzy data alone;

2. In the FIM, a single item was considered for solving a single period SES problem. In the FSIM, single/multiple item(s) are considered for solving multiple-period the SES problem. The order requirements of manufacturing companies in different time periods can change, so this model enables us to analyse variations in order requirements and to take them into account when solving the SES problem;
3. In the FIM, no discount rates were considered in solving the SES problem, as the participating manufacturing companies did not report any such discounts being offered by suppliers. However, in the FSIM, we can consider quantity and bundling discounts in solving the SES problem since suppliers may offer discounts under certain conditions;
4. In the FIM, transportation alternatives were not considered since the manufacturing companies which considered transportation costs in the purchasing price reported that suppliers used only one type of transportation vehicle. In this chapter (Chapter 5), several transportation alternatives are considered in solving the SES problem as manufacturing companies may be faced with transportation alternatives in certain circumstances; and,
5. Finally, in this chapter, a pre-selection process is used to reduce supplier numbers to a manageable level.

Even though the FSIM is more robust than the FIM, the FSIM was not applied in industry. Structuring and estimating the distribution of FSIM parameters requires substantial set of historical data (Iskander, 2004; Iskander, 2006; Iskander, 2007). However, Turkish textile companies that participated in this study did not want the researcher to access substantial set of historical data. Moreover, these companies

explained that they did not consider quantity, bundling and transportation alternatives in solving the SES problem. Additionally, time constraints prevented the application of the FSIM in the industry since searching of specific companies that would allow the researcher to access data and consider typical discounts and transportation alternatives.

This chapter is organised as follows. Section 5.2 describes the fuzzy stochastic integrated model, including the analysis of capability-based risks and performance-based risks. Section 5.3 presents numerical examples of quantity discounts and bundling discounts in supplier selection to verify the FSIM. Section 5.4 provides a brief summary of the chapter.

5.2 Fuzzy Stochastic Integrated Model (FSIM)

The process starts with the analysis of capability-based risks (using qualitative criteria) such as financial position, volume flexibility, technological capability reputation of the suppliers, compliance with sectoral price and communication issues using FAHP and COPRAS-F techniques. FAHP is used to establish the relative importance of the qualitative criteria used by assigning a weight to each criterion based on the judgement of the decision-maker. COPRAS-F is used to evaluate each supplier against the qualitative criteria used, with scores assigned by the decision-maker. The scores of all decision-makers are aggregated and this aggregated score is used to reduce supplier numbers to a manageable level (pre-selection). The aggregated scores of selected suppliers from pre-selection are used as an objective function coefficient in fuzzy stochastic goal programming (FSGP).

In the mitigation of performance-based risks, FSGP is solved by using Lindo 15 to select preferred suppliers and allocate order quantities for selected suppliers. The expected values of fuzzy coefficients of objective functions (uncertain cost, late delivery percentage and defect percentage) are obtained by using Eqn. 4 in Appendix E. Then,

fuzzy memberships of fuzzy stochastic goals are obtained by using Eqns. 15-16 in Appendix E. The fuzzy memberships of these goals are combined in a single objective programming using a max-min method with stochastic constraints and crisp constraints. This process is used for both quantity discounts and bundling discounts. Table 5.1 presents notations used in the FSIM.

Table 5.1: Notations

Parameters	Definition
t	Total number of suppliers $\left(s \in (1,2,3 \ldots t)\right)$
U_s	The score of s^{th} supplier
a	Decision-maker number
U_{sa}	The score of s^{th} supplier for a^{th} decision-maker
$A\,(U_s)$	Aggregated score of s^{th} supplier
DN	Total decision-maker number
j	Quantity discount number
$\tilde{P}_{sj}$	Fuzzy purchasing price for s^{th} supplier and j^{th} quantity discount
X_{sj}	Order quantity for s^{th} supplier and j^{th} quantity discount
v	Period number
$\widetilde{HC}_v$	Fuzzy holding cost for v^{th} period
I_v	Inventory quantity for v^{th} period
q	Type of truck number
$\widetilde{TC}_{sq}$	Fuzzy transportation cost for s^{th} supplier and q^{th} type of truck
T_{svq}	q^{th} type of truck numbers to transport materials from s^{th} supplier to manufacturing company in v^{th} period
PD	Total quantity discount number
PN	Total period number
TN	Total truck numbers for q^{th} type of truck
$\tilde{L}_{sv}$	Fuzzy late delivery percentage for s^{th} supplier in v^{th} period
X_{sv}	Order quantity for s^{th} supplier in v^{th} period
$\widetilde{DP}_{sv}$	Fuzzy defective percentage for s^{th} supplier in v^{th} period
V_s	Supplier production capacity for s^{th} supplier
α_s	Confidence interval for s^{th} supplier
$\propto_v$	Confidence interval for v^{th} supplier
TCP_{svq}	Product carried using q^{th} type of truck to transport material from s^{th} supplier in v^{th} period
p_{sq}	The capacity of q^{th} type of truck to transport material from s^{th} supplier
$\max(AN_{svq})$	The maximum available q^{th} type of trucks available for the s^{th} supplier to supply the manufacturing company in v^{th} period
IV_{sj}	Maximum purchased quantity from s^{th} supplier in j^{th} quantity discount level
IV_{sj}^*	Slightly less than IV_{sj}
$IV_{s(j-1)}$	The maximum purchased quantity from s^{th} supplier in $j-1^{\text{th}}$ quantity discount level
J_{sj}	Decision variable $\{0,1\}$ for quantity discount
I_{v-1}	Inventory quantity for $v-1^{\text{th}}$ period
Z_1^*	Fuzzy stochastic total purchasing cost objective function for quantity discount
Z_2^*	Fuzzy stochastic late delivered unit objective function for quantity discount
Z_3^*	Fuzzy stochastic defective unit objective function for quantity discount

Z_4	Crisp total purchasing value objective function for quantity discount
n	Product number
PT	Total product number
$\tilde{P}_{sn}$	Fuzzy purchasing price for s^{th} supplier and n^{th} product
X_{snv}	The order quantity for s^{th} supplier for n^{th} product in v^{th} period
S_{sn}	Bundling discount for s^{th} supplier and n^{th} product
BI_s	Decision variable {0,1} for bundling discount
$\widetilde{HC}_{nv}$	Fuzzy holding cost for n^{th} product for v^{th} period
I_{nv}	The inventory quantity for n^{th} product and v^{th} period
$\widetilde{TC}_{snq}$	The fuzzy transportation cost for s^{th} supplier for n^{th} product and q^{th} type of truck
T_{snvq}	q^{th} type of truck numbers to transport material from s^{th} supplier to manufacturing company in v^{th} period, including n^{th} product
$\tilde{L}_{snv}$	The fuzzy late delivery percentage for s^{th} supplier for n^{th} product in v^{th} period
$\widetilde{DP}_{snv}$	The fuzzy defective percentage for s^{th} supplier for n^{th} product in v^{th} period
Z_5^*	Fuzzy stochastic total purchasing cost objective function for bundling discount
Z_6^*	Fuzzy stochastic late delivered unit objective function for bundling discount
Z_7^*	Fuzzy stochastic defective unit objective function for bundling discount
Z_8	Crisp total purchasing value objective function for bundling discount
V_{sn}	The supplier production capacity for s^{th} supplier for n^{th} product
OR_{nv}	The order requirement for n^{th} product in v^{th} period
TCP_{snvq}	The carried n^{th} product by using q^{th} type of truck to transport material from s^{th} supplier in v^{th} period.
p_{sq}	The capacity of q^{th} type of truck to transport materials from s^{th} supplier
$\max(AN_{snvq})$	The maximum available for n^{th} product q^{th} type of truck number to transport material from s^{th} supplier in v^{th} period
$I_{n,v-1}$	The inventory quantity for n^{th} product and $v-1^{th}$ period
$A\ (h_k)$	Aggregated weight for k^{th} objective function
$A^*\ (h_k)$	Normalised aggregated weight for k^{th} objective function
Y	Total number of objective functions
g_r/nh_r	Linear/nonlinear fuzzy membership functions of r^{th} fuzzy stochastic goals
λ_r/λ_l	Satisfaction degrees of r^{th} fuzzy stochastic goals/ l^{th} fuzzy goal
$\mu_l(Z_l(x))$	Fuzzy membership of l^{th} fuzzy goal

5.2.1 Analysis of Capability-based Risks (Qualitative Criteria)

In this section, the aggregated scores of decision-makers for each supplier are discussed. In Chapter 3, the application of Fuzzy AHP and COPRAS-F to deal with qualitative data was described in detail, so these steps are not described again. We start with the output of step 2 (see Eqn. 18 in Chapter 3); this is the score (U_s) of each supplier of each decision-maker; U_{sa} presents score of s^{th} supplier for a^{th} decision-maker; $A\ (U_s)$ presents aggregated score of s^{th} supplier. Scores from all the decision-makers can be aggregated as:

$$A\,(U_s)=\frac{\sum_{a=1}^{DN} U_{sa}}{DN} \qquad a = 1,2, \dots .DN \quad s = 1,2, \dots .t \qquad (1)$$

These aggregated scores are used to reduce supplier numbers to a manageable level (pre-selection phase). Suppliers with the highest aggregated scores ($A\ (U_s)$) are selected and the aggregated scores of selected suppliers are used as coefficients for maximising the total score of the supplier objective function ($Z_4\ and\ Z_8$) in FSGP for quantity and bundling discounts.

5.2.2 Analysis of Performance-based Risks (Quantitative Criteria)

This section describes the use of FSGP in evaluating supplier performance in uncertain environments. The fuzzy coefficients (pessimistic, most probable and optimistic) can be determined for suppliers based on their historical data or on expert judgements. The FSGP model uses four objective functions including fuzzy coefficients and stochastic goals: the minimisation of total purchasing cost; minimisation of the numbers of units delivered late; minimisation of the number of defective units; and, maximisation of total score including crisp coefficients and fuzzy goal.

5.2.2.1 Conversion of fuzzy and stochastic data

This section details the conversion of fuzzy data (coefficients) and the conversion of stochastic data (goals and constraints) in FSGP. First, fuzzy coefficients will be converted into crisp values (see Eqn. 4 in Appendix E). Then, fuzzy membership functions of fuzzy stochastic goals are obtained (see Eqns. 15-16 in Appendix E). Finally, stochastic constraints will be converted into deterministic constraints using the chance-constrained method. In this section, FSGP models for quantity discounts and bundling discounts are discussed.

5.2.2.1.1 Quantity discount

Suppliers offer this type of discount when the purchasing quantity depends on the order size for the item. FSGP considers quantity discounts when solving the SES

problem. FSGP includes three fuzzy stochastic objective functions, which are minimisation of total purchasing cost, minimisation late delivered units and minimisation of defective units. Eqn. 2 represents the minimisation of total purchasing cost in which $\tilde{P}_{sj}$ is the fuzzy purchasing price for s^{th} supplier and j^{th} quantity discount, $\widetilde{HC}_v$ is the fuzzy holding cost for v^{th} period, $\widetilde{TC}_{sq}$ is the fuzzy transportation cost for s^{th} supplier and q^{th} type of truck, X_{sj} is the order quantity for s^{th} supplier and j^{th} quantity discount, I_v is the inventory quantity for v^{th} period and T_{svq} is q^{th} type of truck numbers to transport materials from s^{th} supplier to manufacturing company in v^{th} period. Mathematically,

$$Min\ Z_1^* = \sum_{s=1}^{t}\sum_{j=1}^{PD} \tilde{P}_{sj} \times X_{sj} + \sum_{v=1}^{PN} \widetilde{HC}_v \times\ I_v + \sum_{s=1}^{t}\sum_{q=1}^{TN}\sum_{v=1}^{PN} \widetilde{TC}_{sq} \times T_{svq}$$

$$q = 1,2, \ldots .TN;\ v = 1,2, \ldots .PN;\ j = 1,2, \ldots .PD;\ s = 1,2, \ldots .t \qquad (2)$$

Eqn. 3 represents the minimisation of late delivered units where $\tilde{L}_{sv}$ is the fuzzy late delivery percentage for the s^{th} supplier in the v^{th} period and X_{sv} is the order quantity for the s^{th} supplier in the v^{th} period.

$$Min\ Z_2^* = \sum_{s=1}^{t}\sum_{v=1}^{PN} \tilde{L}_{sv} \times X_{sv} \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \qquad (3)$$

Eqn. 4 represents the minimisation of defective units where $\widetilde{DP}_{sv}$ is the fuzzy defective percentage for s^{th} supplier in v^{th} period.

$$Min\ Z_3^* = \sum_{s=1}^{t}\sum_{v=1}^{PN} \widetilde{DP}_{sv} \times X_{sv} \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \qquad (4)$$

These three objective functions (Eqns. 2-4) contain fuzzy coefficients and stochastic goals, which are called fuzzy stochastic goals. First, fuzzy coefficients will be converted into crisp coefficients (see Eqn. 4 in Appendix E). Then, fuzzy membership functions of fuzzy stochastic goals are obtained by using Eqns.15-16 in Appendix E. Then, stochastic constraints are converted into deterministic constraints using the chance-constrained method. Finally, crisp coefficients, stochastic goals and fuzzy

membership of fuzzy stochastic goals will be used in a single objective function in Section 5.2.2.3.

This model also considers the fourth objective function (maximising total utility score) including the aggregated crisp coefficient in Eqn. 5. The robustness of suppliers is increased by maximising the score to mitigate capability-based risks. The fourth objective function (Z_4) can be written as:

$$Max\ Z_4 = \sum_{s=1}^{t} \sum_{v=1}^{PN} A\ (U_s) \times X_{sv} \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \quad (5)$$

This objective function only has a fuzzy goal as companies may not have stochastic goals for this objective function. Fuzzy membership of this goal can be obtained (by Eqn. 17 in Appendix E) and then fuzzy membership of this goal is used in a single objective function described in Section 5.2.2.3.

There are stochastic constraints (supplier production capacity and order requirements) in the FSGP model. Stochastic constraints are converted into deterministic constraints using the chance-constrained method. For example, V_s represents the supplier production capacity for the s^{th} supplier and α_s is the confidence interval for the s^{th} supplier.

$$\Pr(\sum_{v=1}^{PN} X_{sv} \leq V_s\ ) \geq \alpha_s \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \quad (6)$$

This constraint is converted into a crisp constraint using the chance-constrained method as follows:

$$\sum_{v=1}^{PN} X_{sv}\ \leq F_{V_s}^{-1}(1 - \alpha_s) \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \quad (7)$$

Eqn. 8 is crisp order requirement constraint, which was converted from a stochastic constraint using the chance-constrained method. OR_v represents the order requirement in v^{th} period and $\propto_v$ is the confidence interval for the v^{th} period.

$$F_{OR_v}^{-1}(\propto_v) \leq\ I_v + \sum_{s=1}^{t} X_{sv} \qquad v = 1,2, \ldots .PN\ ;\ s = 1,2, \ldots .t \qquad (8)$$

Eqn. 9 represents the carried product constraint, where TCP_{svq} is the carried product, by using the q^{th} type of truck to transport material from the s^{th} supplier in the v^{th} period.

$$\sum_{q=1}^{TN} TCP_{svq} = X_{sv} \qquad q = 1,2,\ldots.TN \tag{9}$$

Eqn. 10 represents the truck capacity constraint where p_{sq} is the capacity of the q^{th} type of truck to transport material from the s^{th} supplier.

$$T_{sqv} = \frac{TCP_{svq}}{p_{sq}} \qquad q = 1,2,\ldots.TN \tag{10}$$

Eqn. 11 represents the available truck number constraint where $\max(AN_{svq})$ is the maximum available q^{th} type of truck available for the s^{th} supplier to supply the manufacturing company in the v^{th} period.

$$T_{svq} \leq \max(AN_{svq}) \qquad q = 1,2,\ldots.TN \tag{11}$$

Eqns. 12-14 represent quantity discount constraints. IV_{sj} is the maximum purchased quantity from the s^{th} supplier at the j^{th} quantity discount level. IV^{*}_{sj} is slightly less than IV_{sj} and $IV_{s(j-1)}$ is the maximum purchased quantity from the s^{th} supplier at the $j-1^{\text{th}}$ quantity discount level. J_{sj} is a binary integer variable.

$$J_{sj} \times IV_{s(j-1)} \leq X_{sj} \qquad j = 1,2,\ldots.PD;\ s = 1,2,\ldots.t \tag{12}$$

$$J_{sj} \times IV^{*}_{sj} \geq X_{sj} \qquad j = 1,2,\ldots.PD;\ s = 1,2,\ldots.t \tag{13}$$

$$\sum_{j=1}^{PD} J_{sj} \leq 1 \qquad j = 1,2,\ldots.PD;\ s = 1,2,\ldots.t \tag{14}$$

Eqn. 15 indicates ordering quantities for periods and quantity discounts that can be shown as:

$$\sum_{v=1}^{PN} X_{sv} = \sum_{j=1}^{PD} X_{sj} \qquad j = 1,2,\ldots.PD;\ v = 1,2,\ldots.PN \tag{15}$$

Eqn. 16 represents the product balance constraint that can be represented as:

$$I_v = I_{v-1} + \sum_{s=1}^{t} X_{sv} - F^{-1}_{OR_v}(\propto_v) \qquad s = 1,2,\ldots.t \tag{16}$$

5.2.2.1.2 Bundling discount

In this chapter, bundling discounts are also considered in FSGP. The analysis of capability-based risks will be the same as quantity discount; however, the objective functions and constraints in the analysis of performance-based risks will be changed. Bundling discounts are used in situations where the cost of an item depends on the quantities of other items purchased. In this situation, suppliers offer products in bundles. FSGP considers bundling discounts when solving the SES problem. FSGP includes three fuzzy stochastic objective functions, which are minimisation of total purchasing cost, minimisation late delivered units and minimisation of defective units. Eqn. 17 represents the minimisation of total purchasing cost, indicating a bundling discount in which $\tilde{P}_{sn}$ is the fuzzy purchasing price for the s^{th} supplier and the n^{th} product, S_{sn} is the bundling discount for the s^{th} supplier and the n^{th} product, BI_s is the bundling binary integer for the s^{th} supplier, $\widetilde{HC}_{nv}$ is the fuzzy holding cost for the n^{th} product for the v^{th} period, $\widetilde{TC}_{snq}$ is the fuzzy transportation cost for the s^{th} supplier for the n^{th} product and q^{th} type of truck, X_{snv} is the order quantity for the s^{th} supplier for the n^{th} product in the v^{th} period, I_{nv} is the inventory quantity for the n^{th} product and the v^{th} period and T_{snvq} is the q^{th} type of truck to transport material from the s^{th} supplier to the manufacturing company in the v^{th} period, including the n^{th} product.

$$Min\ Z_5^* = \sum_{s=1}^{t}\sum_{n=1}^{PT}\sum_{v=1}^{PN}\tilde{P}_{sn} \times X_{snv} - \sum_{s=1}^{t}\sum_{v=1}^{PN} S_{sn} \times BI_s \times X_{snv} + \sum_{n=1}^{PT}\sum_{v=1}^{PN}\widetilde{HC}_{nv} \times\ I_{nv} + \sum_{s=1}^{t}\sum_{n=1}^{PT}\sum_{v=1}^{PN}\sum_{q=1}^{TN}\widetilde{TC}_{snq} \times T_{snvq}\quad q = 1,2,\ldots.TN;\ v = 1,2,\ldots.PN;\ n = 1,2,\ldots.PT;\ s = 1,2,\ldots.t \tag{17}$$

Eqn. 18 represents the minimisation of late-delivered units where $\tilde{L}_{snv}$ is the fuzzy late delivery percentage for the s^{th} supplier for the n^{th} product in the v^{th} period and X_{snv} is the order quantity for the s^{th} supplier for the n^{th} product in the v^{th} period.

$$Min\ Z_6^* = \sum_{s=1}^{t}\sum_{n=1}^{PT}\sum_{v=1}^{PN}\tilde{L}_{snv} \times X_{snv}\quad n = 1,2,\ldots.PT; v = 1,2,\ldots.PN\ ; s = 1,2,\ldots.t \tag{18}$$

Eqn. 19 represents the minimisation of defective units where $\widetilde{DP}_{snv}$ is the fuzzy defective percentage for the s^{th} supplier for the n^{th} product in the v^{th} period.

$$Min\ Z_7^* = \sum_{s=1}^{t} \sum_{n=1}^{PT} \sum_{v=1}^{PN} \widetilde{DP}_{snv} \times X_{snv}\ n = 1,2,\dots.PT; v = 1,2,\dots.PN; s = 1,2,\dots.t \quad (19)$$

These three objective functions (Eqns. 17, 18 and 19) contain fuzzy coefficients and stochastic goals. First, fuzzy coefficients are converted into crisp coefficients (see Eqn. 4 in Appendix E). Then fuzzy membership functions of fuzzy stochastic goals are obtained by using Eqns. 15-16 in Appendix E. Then, stochastic constraints will be converted into deterministic constraints using the chance-constrained method. Finally, crisp coefficients, stochastic goals and fuzzy membership of fuzzy stochastic goals will be used in a single objective function in Section 5.2.2.3.

This model also considers a fourth objective function (maximising total score) including the aggregated crisp coefficient equation and a fuzzy goal. The robustness of suppliers is increased by maximising the score to mitigate capability-based risks. The fourth objective function (Z_8) can be written as:

$$Max\ Z_8 = \sum_{s=1}^{t} \sum_{n=1}^{PT} \sum_{v=1}^{PN} A\ (U_s) \times X_{snv}\ n = 1,2,\dots.PT \quad v = 1,2,\dots.PN\ ; s = 1,2,\dots.t \quad (20)$$

Fuzzy membership of this goal can be obtained using Eqn. 17 in Appendix E and then fuzzy membership of this goal is used in a single objective function in Section 5.2.2.3.

Furthermore, there are stochastic constraints (supplier production capacity and order requirement) in the FSGP model. V_{sn} represents the supplier production capacity for the s^{th} supplier for the n^{th} product. This stochastic constraint is defines as follows:

$$\sum_{v=1}^{PN} X_{snv} \leq F_{V_{sn}}^{-1}(1-\alpha_r) \qquad v = 1,2,\dots.PN\ ; s = 1,2,\dots.t \qquad (21)$$

Eqn. 22, which is stochastic constraint, represents the order requirement constraint where OR_{nv} is the order requirement for the n^{th} product in the v^{th} period.

$$F^{-1}_{OR_{nv}}(\propto_r) \leq I_{nv} + \sum_{s=1}^{t} X_{snv} \qquad s = 1,2, \dots . t \tag{22}$$

Eqn. 23 represents the carried product constraint where TCP_{snvq} is the carried n^{th} product using the q^{th} type of truck to transport material from the s^{th} supplier in the v^{th} period.

$$\sum_{q=1}^{TN} TCP_{snvq} = X_{snv} \qquad q = 1,2, \dots . TN \tag{23}$$

Eqn. 24 represents the truck capacity constraint where p_{sq} is the capacity of the q^{th} type of truck to transport materials from the s^{th} supplier.

$$T_{snvq} = \frac{TCP_{snvq}}{p_{sq}} \qquad q = 1,2, \dots . TN \tag{24}$$

Eqn. 25 represents the available truck number constraint where $\max(AN_{snvq})$ is the maximum available for the n^{th} product of the q^{th} type of truck to transport material from the s^{th} supplier in the v^{th} period.

$$T_{snvq} \leq \max(AN_{snvq}) \qquad q = 1,2, \dots . TN \tag{25}$$

Eqn. 26 represents the product balance constraint that can be indicated as:

$$I_{nv} = I_{n,v-1} + \sum_{s=1}^{t} X_{snv} - F^{-1}_{OR_{nv}}(\propto_r) \qquad s = 1,2, \dots . t \tag{26}$$

Eqn. 27 represents bundling of the conditional constraint where BD_{sn} is the minimum quantity of the n^{th} product, which may be purchased from the s^{th} supplier to satisfy the bundling constraint.

$$BD_{sn} \times BI_n - \sum_{v=1}^{PN} X_{snv} \leq 0 \qquad v = 1,2, \dots . PN \text{ ; } s = 1,2, \dots . t \tag{27}$$

The next subsection presents the comparison of objective functions in the FSGP model.

5.2.2.2 Comparison of objective functions

There are four objective functions and they all have different priorities. To identify the priorities of objective functions, weights are required. FAHP is used to identify weights $(h_1, h_2, \dots, h_y)$ of objective functions. Steps of the FAHP have been

presented in Section 3.3.1 in Chapter 3. In this part of the process, the same steps are followed to identify the weights of objective functions for each decision-maker. The weights of the objective functions (see Eqn. 8 in Chapter 3) for each decision-maker are aggregated using the following equation:

$$A\ (h_k)=\frac{\sum_{a=1}^{g} h_{ka}}{g} \qquad a = 1,2, \ldots . DN \quad s = 1,2, \ldots . t \quad (28)$$

In this equation, h_k represents the weight of the k^{th} objective function for each decision-maker; h_{ka} represents the weight of the k^{th} objective function for the a^{th} decision-maker; $A\ (h_k)$ represents aggregated weight for k^{th} objective function. Aggregated weights are normalised as:

$$A^*\ (h_k) = \frac{A\ (h_k)}{\sum_{k=1}^{y} A\ (h_k)} \qquad k = 1,2, \ldots . y \quad (29)$$

These normalised aggregated weights ($A^*\ (h_k)$) are used as the weights for the objective functions in FSGP. The next subsection discusses the method for solving the SES problem using the proposed FSGP model.

5.2.2.3 Solving fuzzy stochastic goal programming

Three objective functions (Eqns. 2-4) for quantity discounts and three objective functions (Eqns. 17-19) for bundling discounts contain fuzzy coefficients and stochastic goals. First, the fuzzy coefficients of these objective functions will be converted into crisp coefficients. Then, fuzzy membership functions (g_r and nh_r) of fuzzy stochastic goals will be added into a single objective programming. Additionally, fuzzy membership ($\mu_l(Z_l(x))$) of fuzzy goals for quantity discounts (Z_4) and for bundling discount (Z_8) will be added into this single objective programming.

After identifying the fuzzy membership of fuzzy stochastic goals and fuzzy goals, the satisfaction degree (λ_r) of fuzzy stochastic goals and satisfaction degree (λ_l) of fuzzy goals can be combined in a single objective function as follows:

$$Max = \lambda_1 \times A^*(h_1) + \lambda_2 \times A^*(h_2) + \cdots + \lambda_y \times A^*(h_y) \quad (30)$$

Normalised aggregated weights (A^* (h_k)) are obtained from Section 5.2.2.2. Fuzzy membership functions (g_r and nh_r) of fuzzy stochastic goals are used in Eqns. 31-32. Moreover, fuzzy membership ($\mu_l(Z_l(x))$) of fuzzy goals is used in Eqn. 33. The satisfaction degree of objective functions (fuzzy stochastic goals and fuzzy goals) can be represented as follows:

$$\lambda_r \leq g_r \qquad r = 1,2,3, \ldots. R \quad (31)$$

$$\lambda_r \leq nh_r \qquad r = 1,2,3, \ldots. R \quad (32)$$

$$\lambda_l \leq \mu_l(Z_l(x)) \qquad l = 1,2,3, \ldots. L \quad (33)$$

$$\lambda_r, \lambda_l \in [0,1] \quad (34)$$

For solving quantity discount problem, Eqns. 31-33, supplier production capacity (Eqn. 7), order requirement constraint (Eqn. 8), carried product constraint (Eqn. 9), truck capacity constraint (Eqn. 10), truck number constraint (Eqn. 11), quantity discount constraint (Eqns. 12-14), balanced ordering quantity constraint (Eqn. 15) and product balanced constraint (Eqn. 16) will be the constraints in the single objective programming. With this step, the process of identifying preferred suppliers, and order allocation to these suppliers, is concluded for situations involving quantity discounts.

For solving bundling discount problems, Eqns. 31-33, supplier production capacity (Eqn. 21), order requirement constraint (Eqn. 22), carried product constraint (Eqn. 23), truck capacity constraint (Eqn. 24), truck number constraint (Eqn. 25), product balance constraint (Eqn. 26) and bundling conditional constraint (Eqn. 27) will be the constraints in the single objective programming. With this step, the process of identifying preferred suppliers, and order allocations to these suppliers, is concluded for situations involving bundling discount. Next section will present numerical examples for quantity discounts and bundling discounts.

5.3 Numerical Examples

Fuzzy stochastic goal programming (FSGP) is applied to a numerical dataset for quantity discount problems and bundling discount problems. In these numerical examples, two companies are considered in which a SES problem is to be solved in situations involving quantity discounts and bundling discounts. These numerical examples use artificial dataset to test the FSIM in simulated environment. One of two companies wishes to purchase fabric from ten suppliers in quantity discount environment. The other company wishes to purchase fabric and yarn from ten suppliers. Additionally, the individual methods/techniques used are generic enough to be applied to real world problems, with minor adjustments. Next subsection will present a numerical example of a quantity discount.

5.3.1 Numerical Example for Quantity Discount

In the following numerical example, Company AB, which is a textile manufacturing company, has to minimise purchasing costs, numbers of late delivered units and numbers of defective units when purchasing fabric. The managers of the company decide to screen the capabilities of suppliers to reduce supplier numbers to a manageable level. After this, managers request information about the estimated costs of fabric, estimated late delivery percentages, estimated defect percentages, stochastic capacity and the offers of suppliers for quantity discounts from pre-selected suppliers (after pre-selection). The managers of the buyer company determine their stochastic goals and order requirements for different periods from historical data and they determine fuzzy goal for qualitative data based on their experience. The process of supplier selection starts with the pre-selection phase.

5.3.1.1 Pre-selection phase for quantity discount

The pre-selection phase includes fuzzy AHP (FAHP) and fuzzy COPRAS (COPRAS-F). Four managers of the company, including the purchasing manager, financial manager, planning manager and quality manager evaluate the capability of suppliers against qualitative criteria. FAHP was used to determine the weight of each qualitative criterion (see Eqn. 9 in Chapter 3). Linguistic weights for qualitative criteria for each manager are indicated in Table 1F in Appendix F. The weights for qualitative criteria for each manager are indicated in Table 5.2.

Table 5.2: The normalised weights (w_i^*) of qualitative criteria

Criteria \ Managers	Purchasing Manager	Financial Manager	Planning Manager	Quality Manager
Financial Position	0.21	0.20	0.19	0.16
Volume Flexibility	0.17	0.20	0.15	0.18
Technological Capability	0.16	0.18	0.16	0.21
Reputation	0.14	0.17	0.16	0.16
Compliance with Sectoral Price	0.16	0.12	0.16	0.13
Communication Issues	0.16	0.13	0.17	0.16
CR ≤ 0.1	0.046	0.055	0.043	0.053

Based on the w_i^* of the purchasing manager in Table 5.2, the importance of qualitative criteria are, in order: financial position > volume flexibility > technological capability = compliance with sectoral price = communication issues> reputation.

These weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of all managers for evaluating supplier performance using qualitative criteria are indicated in Table 2F of Appendix F. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 5.3.

Table 5.3: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Managers	Purchase Manager	Financial Manager	Planning Manager	Quality Manager	Aggregated Score
Supplier 1	0.7429	0.9161	0.9235	0.7170	0.8249
Supplier 2	0.8634	0.8506	0.8704	0.7064	0.8227
Supplier 3	0.8237	0.8126	0.7796	0.6770	0.7732
Supplier 4	0.7747	0.8126	0.9252	0.6770	0.7974

Supplier 5	0.8615	0.9161	0.8745	0.7304	0.8456
Supplier 6	0.9592	0.8705	0.8355	0.7464	0.8529
Supplier 7	1.0000	1.0000	1.0000	1.0000	1.0000
Supplier 8	0.8996	0.9161	0.9594	0.7994	0.8936
Supplier 9	0.8996	0.9161	0.9996	0.7648	0.8950
Supplier 10	0.7475	0.8855	0.8205	0.7163	0.7924

Aggregated scores of suppliers are used to remove low-performance suppliers from the list of suppliers. Managers of company have decided to pre-select the five suppliers with the highest scores for the evaluation phase. Therefore, Supplier 7, Supplier 8, Supplier 9, Supplier 6 And Supplier 5 are chosen for the evaluation phase for quantity discounts to select preferred suppliers and allocate orders to these selected suppliers.

5.3.1.2 Evaluation phase for quantity discount

The performance of pre-selected suppliers and their estimated costs for fabric, estimated late delivery percentages, estimated defective percentages and stochastic capacities are evaluated in this phase. All data for this phase used in FSGP are indicated in Tables 3F-9F in Appendix F. For example, stochastic capacity of Supplier 5 is normally distributed with median value and standard deviation being 2400 and 100, respectively. The normalised aggregated weights $A^*(h_y)$ of the objective functions are given in Table 5.4.

Table 5.4: The normalised aggregated weights ($A^*(h_y)$) of objective functions

Managers / Objective Functions	Purchase Manager	Financial Manager	Planning Manager	Quality Manager	Aggregated Weights	Normalised Aggregated Weights
Total Cost	0.33	0.29	0.25	0.30	0.29	0.29
Late Delivery	0.28	0.29	0.25	0.30	0.28	0.28
Defect Percentage	0.25	0.29	0.25	0.24	0.26	0.25
Total Score	0.15	0.15	0.25	0.18	0.18	0.18
CR ≤ 0.1	0.049	0.044	0.031	0.050	-	-

The fuzzy stochastic goals (Z_1^*, Z_2^*, Z_3^*) and fuzzy goal (Z_4), together with the supplier production capacity (Eqn. 7), order requirement constraint (Eqn. 8), carried product constraint (Eqn. 9), truck capacity constraint (Eqn. 10), truck number constraint (Eqn. 11), quantity discount constraints (Eqns. 12-14), balanced ordering quantity constraint (Eqn. 15), product balanced constraint (Eqn. 16), the normalised aggregated weights $A^*(h_y)$ of the objective function are then used in a single objective programming to select preferred suppliers and to allocate orders. The order quantities for suppliers in particular periods are indicated in Table 5.5.

Table 5.5: Order quantities (X_{sv}) for suppliers in periods

Periods / Suppliers	Period 1	Period 2	Period 3
Supplier 5	0	0	0
Supplier 6	0	911	0
Supplier 7	0	590	2,167
Supplier 8	1,106	1,022	0
Supplier 9	1,535	593	0

As demonstrated by the results presented in Table 5.5, Supplier 5 is not selected for any period. Supplier 6 is not selected in period 1 and 3; however, 911 units from Supplier 6 are purchased in period 2. Supplier 7 is not selected in period 1; however, 590 and 2,167 units from Supplier 7 are purchased in periods 2 and 3 respectively. Supplier 8 is not selected in period 3; however, 1,106 and 1,022 units from Supplier 8 are purchased in periods 1 and 2 respectively. Supplier 9 is not selected in period 3; however, 1,535 and 593 units from Supplier 9 are purchased in periods 1 and 2 respectively.

This model also assigns order quantities to truck alternatives. Transportation alternatives selected by model are shown in Table 5.6.

Table 5.6: Truck alternatives (T_{svq}) for periods

Suppliers	Truck Types	Period 1	Period 2	Period 3
Supplier 5	Truck 1	0	0	0
	Truck 2	0	0	0

	Truck 3	0	0	0
Supplier 6	Truck 1	0	0	0
	Truck 2	0	12	0
	Truck 3	0	0	0
Supplier 7	Truck 1	0	4	2
	Truck 2	0	2	12
	Truck 3	0	2	11
Supplier 8	Truck 1	0	0	0
	Truck 2	1	0	0
	Truck 3	12	11	0
Supplier 9	Truck 1	1	1	0
	Truck 2	5	1	0
	Truck 3	12	6	0

The objective function values and associated weights for the solution described above is shown in Table 5.7.

Table 5.7: Objective function values and associated weights of the proposed solution

Goals and Satisfaction Degrees	**Results**
Total Cost	52,137
Late Delivered Units	475
Defective Units	498
Total Score	7,341
λ_1	1
λ_2	0.83
λ_3	1
λ_4	0.89

As demonstrated by the results presented in Table 5.7, the total cost of purchasing is $52,137. Four-hundred and seventy-five (out of 7,924) units are delivered late and 498 (out of 7,924) units are defective. The total score, which indicates robustness of supplier to mitigate capability-based risks, is 7,341. The satisfaction degrees of first and fourth objective functions (Z_1^*, Z_4) are fully satisfied, and the degrees of satisfaction for the second and third objective (Z_2^*, Z_3^*) functions are partly satisfied using the FSIM.

5.3.2 Numerical Example for Bundling Discount

In this numerical example for a bundling discount, Company CD, which is a textile manufacturing company, wants to purchase fabric and yarn from suppliers. The managers of the company decide to screen suppliers based on their capabilities in order

to reduce supplier numbers to a manageable level. After this, the managers request information about estimated costs of fabric, estimated late delivery percentages, estimated percentages of defects, stochastic capacity and bundling discounts conditions from pre-selected suppliers (after pre-selection). The managers of the buyer company determine the stochastic goals of this company from historical data and they determine fuzzy goals for qualitative data based on their experience. The process of supplier selection begins with the pre-selection phase.

5.3.2.1 Pre-selection phase for bundling discount

The pre-selection phase has been described in Section 5.3.1.1. Linguistic weights of qualitative criteria for managers of the company are indicated in Table 10F in Appendix F. The weights for qualitative criteria for each manager are indicated in Table 5.8. Based on the w_i^* of the financial manager in Table 5.8, the importance of qualitative criteria are, in order: financial position > technological capability > volume flexibility = communication issues> compliance with sectoral price >reputation.

Table 5.8: The normalised weights (w_i^*) of qualitative criteria

Managers / **Criteria**	**Financial Manager**	**Purchase Manager**	**Planning Manager**	**Quality Manager**
Financial Position	0.21	0.23	0.21	0.24
Volume Flexibility	0.16	0.17	0.17	0.16
Technological Capability	0.19	0.15	0.18	0.15
Reputation	0.13	0.16	0.13	0.15
Compliance with Sectoral Price	0.15	0.16	0.15	0.16
Communication Issues	0.16	0.13	0.16	0.15
CR $\leq$ 0.1	0.036	0.058	0.065	0.047

These normalised weights (w_i^*) for qualitative criteria are then used to derive supplier scores (U_s) using COPRAS-F. Linguistic scores of all managers for evaluating supplier performance using qualitative criteria are indicated in Table 11F in Appendix F. The corresponding crisp scores (U_s) for each supplier against qualitative criteria are shown in Table 5.9.

Table 5.9: Scores of suppliers (U_s) under qualitative criteria

Suppliers \ Managers	**Financial Manager**	**Purchasing Manager**	**Planning Manager**	**Quality Manager**	**Aggregated Score**
Supplier 1	0.9140	0.9963	0.9045	0.8445	0.9148
Supplier 2	0.8008	0.8342	0.9757	0.8735	0.8710
Supplier 3	0.9075	0.9382	0.9385	0.8445	0.9072
Supplier 4	0.8512	0.8807	0.9759	0.8946	0.9006
Supplier 5	0.8993	0.8799	0.8836	0.7859	0.8622
Supplier 6	0.9025	0.8836	0.8181	0.9017	0.8765
Supplier 7	0.9090	0.8471	0.8796	0.8536	0.8723
Supplier 8	0.9001	0.9701	0.9501	0.9435	0.9410
Supplier 9	1.0000	1.0000	0.8390	1.0000	0.9597
Supplier 10	0.8465	0.9122	1.0000	0.8759	0.9086

Aggregated scores of suppliers are used to remove low-performing suppliers from the list of suppliers. Managers of Company CD have decided to pre-select the five suppliers with the highest scores for the evaluation phase. Therefore, the performances of Supplier 1, Supplier 3, Supplier 8, Supplier 9 and Supplier 10 are considered in the evaluation phase for bundling discounts to select preferred suppliers and allocate orders to selected suppliers.

5.3.2.2 Evaluation phase for bundling discount

The performance of pre-selected suppliers and their estimated costs, estimated late delivery percentages, estimated defective percentages and stochastic capacities for both fabric and yarn are evaluated in this phase. All data for this phase used in FSGP are indicated in Tables 12F-21F in Appendix F. For example, stochastic capacity of Supplier 1 is normally distributed with median value and standard deviation being 2500 and 200, respectively. The normalised aggregated weights $A^*(h_y)$ of the objective functions are given in Table 5.10.

Table 5.10: The normalised aggregated weights ($A^{*}(h_y)$) of objective functions

Managers / Objective Functions	Financial Manager	Purchasing Manager	Planning Manager	Quality Manager	Aggregated Weights	Normalised Aggregated Weights
Total Cost	0.24	0.25	0.24	0.34	0.27	0.27
Late Delivery Percentage	0.30	0.25	0.30	0.21	0.26	0.26
Defect Percentage	0.30	0.25	0.24	0.21	0.25	0.25
Total Score	0.18	0.25	0.21	0.24	0.22	0.22
CR ≤ 0.1	0.061	0.042	0.025	0.062	-	-

The fuzzy stochastic goals (Z_5^*, Z_6^*, Z_7^*) and fuzzy goal (Z_8) together with the supplier production capacity (Eqn. 21), order requirement constraint (Eqn. 22), carried product constraint (Eqn. 23), truck capacity constraint (Eqn. 24), truck number constraint (Eqn. 25), product balance constraint (Eqn. 26) and bundling conditional constraint (Eqn. 27), and the normalised aggregated weights $A^*(h_y)$ of the objective function are then used in the single objective programming to select preferred suppliers and to allocate orders. The order quantities for suppliers in particular periods, which are crisp values, are indicated in Table 5.11.

Table 5.11: Order quantities (X_{snv}) for suppliers in periods

Products	Periods / Suppliers	Period 1	Period 2	Period 3
Product 1	Supplier 1	4	0	25
	Supplier 3	0	0	25
	Supplier 8	0	959	1,171
	Supplier 9	2,001	0	25
	Supplier 10	124	671	12
Product 2	Supplier 1	0	0	403
	Supplier 3	0	0	0
	Supplier 8	668	0	0
	Supplier 9	0	1,411	403
	Supplier 10	1,404	0	836

As demonstrated by the results presented in Table 5.11, Supplier 1 is not selected for product 1 (fabric) in period 2; however, 4 and 25 units from Supplier 1 are purchased in periods 1 and 3 respectively. Supplier 3 is not selected for product 1 (fabric) in periods 1 and 2; however, 25 units from Supplier 3 are purchased in period 3. Supplier 8 is not selected for product 1 (fabric) in period 1; however, 959 and 1,171 units from Supplier 8 are purchased in periods 2 and 3 respectively. Supplier 9 is not selected for product 1 (fabric) in period 2; however, 2,001 and 25 units from Supplier 9 are purchased in periods 1 and 3 respectively. Supplier 10 is selected for all periods for product 1 (fabric) and 124, 671 and 12 units are purchased for periods 1, 2 and 3 respectively.

Supplier 3 is not selected for product 2 (yarn) in any period. Supplier 1 is not selected for product 2 (yarn) in periods 1 and 2; however, 403 units from Supplier 1 are purchased in period 3. Supplier 8 is not selected for product 2 (yarn) in periods 2 and 3; however, 668 units from Supplier 8 are purchased in period 1. Supplier 9 is not selected for product 2 (yarn) in period 1; however, 1,411 and 403 units from Supplier 9 are purchased in periods 2 and 3 respectively. Supplier 10 is not selected for product 2 (yarn) in period 2; however, 1,404 and 836 units from Supplier 10 are purchased in periods 1 and 3 respectively. In the purchasing of product 1 (fabric), the buyer company may not face issues as it purchases fabric from at least two suppliers in all periods. However, the buyer company may face some problems while purchasing product 2 (yarn), since it purchases yarn from only Supplier 9 in period 2.

This model also assigns order quantity to truck alternatives. Transportation alternatives selected by the model are shown in Table 5.12.

The objective function values and associated weights for the solution described above are shown in Table 5.13.

Table 5.12: Truck alternatives (T_{snvq}) for products and periods

Products	Suppliers	Truck Types	Period 1	Period 2	Period 3
Product 1	Supplier 1	Truck 1	1	0	1
		Truck 2	0	0	0
		Truck 3	0	0	0
	Supplier 3	Truck 1	0	0	1
		Truck 2	0	0	1
		Truck 3	0	0	0
	Supplier 8	Truck 1	0	0	0
		Truck 2	0	0	0
		Truck 3	0	10	12
	Supplier 9	Truck 1	9	0	1
		Truck 2	12	0	0
		Truck 3	6	0	0
	Supplier 10	Truck 1	1	12	1
		Truck 2	1	0	0
		Truck 3	1	0	0
Product 2	Supplier 1	Truck 4	0	0	2
		Truck 5	0	0	2
	Supplier 3	Truck 4	0	0	0
		Truck 5	0	0	0
	Supplier 8	Truck 4	4	0	0
		Truck 5	2	0	0
	Supplier 9	Truck 4	0	5	2
		Truck 5	0	7	2
	Supplier 10	Truck 4	11	0	7
		Truck 5	3	0	1

Table 5.13: The results of model

Goals and Satisfaction Degrees	**Results**
Total Cost	34,345
Late Delivered Units	355- product 1 and 324- product 2
Defective Units	223- product 1 and 178- product 2
Total Score	9,504
λ_1	1
λ_2	1
λ_3	1
λ_4	1

As demonstrated by the results presented in Table 5.13, total cost of purchasing is $34,345. Three-hundred and fifty-five (out of 5,017) units for product 1 (fabric) and 324 (out of 5,125) units for product 2 (yarn) are delivered late and 223 (out of 5,017) units for product 1 (fabric) and 178 (out of 5,125) units for product 2 (yarn) are defective. The total score, which indicates the robustness of suppliers to mitigate

capability-based risks, is 9,504. The degrees of satisfaction $(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$ of each objective function for each manager are fully satisfied based on the FSIM.

5.4 Summary

This chapter proposed a comprehensive fuzzy stochastic integrated model (FSIM) to mitigate capability-based and performance-based risks for quantity and bundling discount problems in SES. Many studies in the literature have focused on solving the SES problem. However, most of these studies do not completely take account of uncertainties in the environment including those found in qualitative, fuzzy and stochastic (quantitative) data. The FSIM adapts to the uncertain environment and adapts to stochastic data. The FSIM in this chapter considers quantity and bundling discounts in solving the SES problem. Moreover, the FSIM takes into account transportation alternatives, which have been considered in the literature. The FSIM consists of two major phases, which are pre-selection and evaluation. FAHP and COPRAS-F are used to reduce the number of suppliers to a manageable level (pre-selection) and the resultant aggregate weighted scores (representing all qualitative criteria) (obtained in COPRAS-F) for pre-selected suppliers are used as objective function coefficients in the fuzzy stochastic goal programming model. Then, the fuzzy coefficients of each objective function (uncertain cost, late delivery percentage and defect percentage) are converted into crisp coefficients. After that, FAHP is used to obtain weights for objective functions (uncertain cost, late delivery percentage and defect percentage and supplier capability criteria). The weights representing the relative importance of these criteria are used as objective function coefficients in the fuzzy stochastic goal programming model. Objective functions (goals) and stochastic constraints (supplier capacity and order requirement) are analysed to select the best suppliers and allocate orders for these suppliers. This process is used for both bundling

and quantity discount problems in supplier selection. The next chapter presents the discussion of results together with research contributions and future directions.

6 DISCUSSION AND CONCLUSIONS

6.1 Introduction

The literature associated with supplier evaluation and selection (SES) problem has been reviewed in this thesis in order to identify research gaps. The literature review revealed that the limited number of studies that have considered the operational risks associated with the SES problem do not provide comprehensive solution approaches. For instance, most studies only take into account the variability associated with tangible attributes and they do not consider intangible attributes in the evaluation and selection of suppliers. Several studies have analysed the uncertainty induced by imprecise data associated with supplier performance. Firms deal with three main forms of imprecise data: qualitative (linguistic) data, fuzzy data and stochastic (quantitative) data. Most studies have taken into account qualitative, fuzzy and stochastic data to mitigate uncertainty effects. However, the types of imprecise data available may vary depending on the differences in the decision environment. For instance, most manufacturing companies would be able to use both fuzzy and stochastic (quantitative) data. As such, to solve the SES problem, a comprehensive model with the capacity to handle qualitative, fuzzy and stochastic data is required. Additionally, most previous studies have selectively used other factors such as transportation alternatives, and discounts in their SES models. Moreover, only a few studies have validated their models using empirical data. Considering these limitations, this thesis undertook to develop a comprehensive decision support model that can be used to mitigate operational risks associated with the SES problem while also accounting for multiple situational factors.

The proposed integrated model consists of two modules, namely the fuzzy integrated model (FIM) and the fuzzy stochastic integrated model (FSIM), each of

which aims to mitigate capability-based and performance-based risks under different scenarios. The former model, FIM, was validated using empirical data drawn from eight Turkish textile companies in relation to solving their SES problems. Furthermore, the results generated using the FIM were compared with the outcomes of the SES process used by each company to test the model. The results confirmed that the companies involved would have benefitted from using the proposed model in terms of savings in purchasing costs, improved delivery times and reductions in the numbers of defective items delivered. For example, if Company A’s purchased order quantities had been generated using the FIM, it would have been able to save 6.9 % of the total purchasing cost and could have reduced the number of late delivered units by 22.6% and defective units by 21.5 %. Similarly, Company B would have saved 2.5 % of the total purchasing costs while achieving improvements of 3.7% in delayed units and 4.4% in defective units. The other companies would have achieved comparable savings in purchasing costs with the highest proportion of savings amounting to 12.1 % of total purchasing costs achieved by Company C. Additionally, the application of the FIM in Company G resulted in a reduction of 39.5% in the number of delayed units. The greatest reduction in defective units delivered (21.5%) by using the proposed model was achieved by Company A. Thus, the efficacy and superiority of the proposed FIM was confirmed through the results of its application in all eight Turkish textile companies.

The feasibility of the FIM was evaluated through a questionnaire survey administered among supply chain managers using a Likert scale which consisted of a three-scale range: 0 (not at all feasible), 5 (partially feasible) and 10 (completely feasible). Managers of the companies surveyed were requested to assign a number (between 0 and 10) to four questions (See Appendix C). The managers’ average feasibility scores for the supplier selection criteria used in the model varied between 7.5

and 9, scores for objectives used in the model varied between 7 and 10, scores for suppliers selected using the FIM varied between 8 and 9 and scores for the results (Total Purchasing Cost, Late Delivered Units, and Defective Units) of the model varied between 8 and 9.2. This means that the criteria and objectives used in the proposed model, as well as the suppliers selected and the overall results generated (Total Purchasing Cost, Late Delivered Units, and Defective Units) were highly useful and relevant for the companies surveyed. The highest average feasibility scores for the supplier selection criteria used in the model was 9 in the responses received from Company F and Company H. The highest average feasibility score for the objectives used in the model was 10, which was assigned by a purchasing manager of Company B. The highest average feasibility scores for the suppliers selected using the FIM was 9, which were assigned by the managers of Company B and G. The highest average score for the feasibility of the results of the model was 9.2, which was assigned by managers of Company F. It can be concluded that all managers rated the proposed model and its results as extremely useful.

Additionally, the FIM was compared with possibilistic integrated model (PIM) including FAHP, FTOPSIS and possibilistic linear programming (PLP) to test effectiveness of the FIM. The FIM and the PIM are used to solve SES problem for only one company (i.e. Company D). First of all, the results of FTOPSIS and COPRAS-F will be compared to test the effectiveness of COPRAS-F. The performance of COPRAS-F is better than the performance of FTOPSIS in terms of results of these two models. Moreover, PLP and FLP were compared to test effectiveness of the FLP. The results of PLP are $13,112,500 cost, 425,500 late delivered units and 86,883 defective units. The results of FLP are $13,000,000 cost, 425,000 late delivered units and 84,500 defective units. It can be seen that if PLP were used to solve SES problem for Company

D, it would have been able to renounce $112,500 (out of $ 13,000,000) of the total purchasing cost and it would have been able to purchase 500(out of 425,000) more late delivered units and 2,383 (out of 84,500) more defective units. It can be said that the FIM, which was used to solve SES problem in this thesis, is more effective than the PIM.

The FSIM developed in Chapter 5 was verified by using two numerical examples representing different discount conditions. In the first example, one company wished to purchase fabric from ten suppliers under quantity discount conditions. First, the managers of the company screened the capabilities of suppliers to make a shortlist of suppliers. In the pre-selection phase, aggregated scores of the decision-makers for each supplier were used to reduce the number of suppliers. In the evaluation phase, suppliers were selected and orders were allocated for these suppliers. In this example, total cost of purchasing was $52,137. Four hundred and seventy-five (out of 7,924), units were delivered late and 498 (out of 7,924) units were defective. The total score, which indicates the robustness of the supplier to mitigate capability-based risks, is 7,341. The degrees of satisfaction of the two objective functions (late delivered units and total score) were partly (0.83 and 0.89) satisfied. However, two objective functions (total purchasing cost and defective units) were fully (1.0) satisfied. Thus, it can be said that the FSIM can be useful for companies making use of quantity discounts.

In the second example, the FSIM was used to address a SES problem in a bundling discount situation. In this example, one company wished to purchase fabric and yarn from ten suppliers. Again, a pre-selection phase was used to reduce the number of suppliers before undertaking detailed evaluations. In this example, total cost of purchasing was $34,345. Three hundred and fifty-five (out of 5,017) units for product 1 (fabric) and 324 (out of 5,125) units for product 2 (yarn) were delivered late and 223

(out of 5,017) units for product 1 (fabric) and 178 (out of 5,125) units for product 2 (yarn) units were defective. The degrees of satisfaction of all objective functions (total purchasing cost, late delivered units, defective units and total score) were one (1.0). Therefore, it can be concluded that the proposed FSIM can be extremely useful for companies purchasing under bundling discount conditions.

6.2 Research Contributions

This study developed two mathematical models to support SES decisions: the fuzzy integrated model (FIM) and the fuzzy stochastic integrated model (FSIM).

The FIM includes FAHP to establish the relative importance of the defined qualitative criteria/objective functions, COPRAS-F to evaluate supplier capability with respect to capability-based (qualitative criteria) risks, the signed distance method to convert fuzzy numbers into crisp numbers, and FLP to solve the problem of supplier selection and order allocation using the max-min method. FIM's contribution to knowledge is to consider both capability-based (qualitative criteria) and performance-based (quantitative criteria) risks in solving the SES problem. Moreover, the FIM can be useful for companies that wish to purchase single items covering single periods. Additionally, this model is user-friendly as it enables decision-makers to compare criteria (qualitative) and objectives used in the model and to assign fuzzy numbers (quantitative criteria). The contribution of FIM for practice is shown by the fact that it was able to process the supplier selection dataset from eight Turkish textile companies (including twenty-four managers) which validated its use comprehensively. The results of the FIM testing mentioned above prove that this model enables companies to reduce total purchasing costs, and minimise the numbers of late delivered units and defective units and is extremely useful for companies. Companies, which have participated in this study, did not use any additional criteria that were not included in the questionnaire.

However, if these companies used any additional criteria then the FIM would have been able to account for such criteria without any difficulty. Additionally, cost, late delivery percentage and defect percentage are the criteria most commonly considered by many companies to solve the SES problem. Moreover, the feasibility of the criteria and objectives used in the FIM has been very high, according to the survey results. That is; criteria and objectives used in the FIM are suitable and relevant for the companies participated in this study.

In the fuzzy stochastic integrated model (FSIM), FAHP and COPRAS-F are used to reduce the number of possible suppliers to a manageable level with respect to capability-based (qualitative criteria) risks and fuzzy stochastic goal programming (FSGP) is used to mitigate performance-based risks and to select preferred suppliers and to allocate orders. The FSIM's contribution to knowledge is its ability to deal with qualitative, fuzzy (coefficients) and stochastic (goals) quantitative data simultaneously. Therefore, this model enables companies which have stochastic goals to solve the SES problem while considering a wide range of variables. Moreover, the inclusion of stochastic data into FSIM provides more robust and effective solutions than fuzzy data alone. The other contribution of this model is that it can deal with multiple items and multiple time periods to solve the stochastic the SES problem. For many companies order requirements can vary in different periods, so the FSIM can be useful in considering the variability associated with order requirements. Moreover, the FSIM takes into account quantity and bundling discounts in solving the SES problem since suppliers may offer different discounts under different conditions. As such the FSIM can be helpful for companies that wish to order single or multiple items and consider quantity or bundling discounts. Furthermore, the FSIM can take in to account several transportation alternatives in solving the SES problem. The FSIM can be helpful for

companies to evaluate suppliers that deliver materials using different transportation alternatives. Moreover, the FSIM integrates stochastic goals and fuzzy goals to address the SES problem. Therefore, the FSIM offers a means of obtaining comprehensive solutions considering both stochastic and fuzzy goals. Finally, the FSIM is useful in group decision-making situations as the individual scores of several managers can be aggregated with the use of COPRAS-F and FAHP.

Overall, the FIM and FSIM provide new and complementary perspectives for solving decision-making and optimisation problems. For example, the FIM offers a simple and efficient way to solve any multi-objective linear problem, such as supply chain optimisation, logistics network design and aggregate production planning problems. In effect, the FSIM serves as a robust tool to solve advanced multi-objective non-linear problem involving stochastic goals, fuzzy coefficients and qualitative data.

6.3 Directions for Future Research

This study has delivered significant research findings related to solve the SES problem. Future research, building on these findings, may address a number of SES issues that are yet to be resolved. For instance, disruption risks have not been considered in this study. Future research could consider and mitigate this type of risks in the SES problem. Additionally, the effects of disruption risks can be easily accounted for by adding an objective function in the models proposed in this thesis. The FIM was applied in eight Turkish textile companies to validate the model. This model could be applied in different industries, such as the automobile industry or different sectors, such as the service, public and e-procurement sectors. Moreover, this model could be applied to textile industries in different countries. Comparative and collective findings of such studies can be used to further refine the model proposed in this thesis and enhance its generalisability. Additionally, future research could conduct sensitivity analysis on the

proposed models with changing weights of criteria, score of suppliers and weights of objective functions. The proposed model has considered the relationship between single buyers and multiple suppliers to solve the SES problem. Extensions of this model could take into account the relationship between multiple buyers and multiple suppliers in addressing the SES problem. The FSIM was not applied in practice to test its feasibility and the superiority. Future research could apply this model in practical situations for further validation of the model. Additionally, the FSIM is able to consider truck alternatives. Freight rates for different transportation alternatives (ships, trains or planes) can be added into the proposed model. Moreover, the FSIM can be extended to include less-than-truck-load (LTL) situations. Both stochastic coefficients and fuzzy goals may need to be considered in solving the SES problem under such situations. Therefore, companies which have stochastic data (coefficients) and fuzzy data (goals) can find this model particularly useful. For example, soft issues associated with the SES problem, such as trust and visibility can be considered in solving the SES problem with appropriate minor modification to the proposed model.

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APPENDIX A: ETHICS CONFIRMATION

UNIVERSITY OF WOLLONGONG

In reply please quote: HE13/065

15 March 2013

Mr Alptekin Uluta
3/2 College Place
WOLLONGONG NSW 2500

Dear Mr Uluta

Thank you for your response dated 11 March 2013 to the HREC review of the application detailed below. I am pleased to advise that the application has been approved.

Ethics Number:	HE13/065
Project Title:	Data-driven Risk Management in Supplier Selection for Turkish Textile Industry
Researchers:	Mr Alptekin Ulutas, Dr Senevi Kiridena, A/Prof Peter Gibson, Dr Nagesh Shukla
Approval Date:	14 March 2013
Expiry Date:	13 March 2014

The University of Wollongong/Illawarra Shoalhaven Local Health District Social Sciences HREC is constituted and functions in accordance with the NHMRC *National Statement on Ethical Conduct in Human Research*. The HREC has reviewed the research proposal for compliance with the *National Statement* and approval of this project is conditional upon your continuing compliance with this document.

A condition of approval by the HREC is the submission of a progress report annually and a final report on completion of your project. The progress report template is available at http://www.uow.edu.au/research/rso/ethics/UOW009385.html. This report must be completed, signed by the appropriate Head of School, and returned to the Research Services Office prior to the expiry date.

As evidence of continuing compliance, the Human Research Ethics Committee also requires that researchers immediately report:

- proposed changes to the protocol including changes to investigators involved
- serious or unexpected adverse effects on participants
- unforseen events that might affect continued ethical acceptability of the project.

Please note that approvals are granted for a twelve month period. Further extension will be considered on receipt of a progress report prior to expiry date.

If you have any queries regarding the HREC review process, please contact the Ethics Unit on phone 4221 3386 or email rso-ethics@uow.edu.au.

Yours sincerely

Garry Hoban

A/Professor Garry Hoban
Chair, Social Sciences
Human Research Ethics Committee

Ethics Unit, Research Services Office
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APPENDIX B: SUPPLIER PERFORMANCE QUESTIONNAIRE

THE QUESTIONNAIRE FOR EVALUATION OF SUPPLIER PERFORMANCE

COMPANY CODE NAME:

POSITON OF RESPONDENT:

DATE:

INTRODUCTION

This questionnaire is intended to be completed by selected management staff of Turkish textile companies to provide information that will help quantify the impact of risks in the supplier selection process. Questions represent two types of risk: performance-based risks (uncertain cost, uncertain delivery time, uncertain defect rate, uncertain demand and uncertain capacity) and capability-based risks (financial position, time flexibility, technological capability, reputation, compliance with price and communication issues). Please note that descriptions of the supplier selection criteria used are provided in Table 2 and Table 3 .

INSTRUCTION

You may choose not to answer any or all of the questions. If you do not wish to answer a question, please skip that question and proceed to the next question.

This questionnaire consists of six sections.

- **First section includes questions relating to general information about the procurement process of the company.**
- **Second section involves objectives of the model. In this section, Linguistic Variables (extremely important, very important, important, moderately important, and equally important) are illustrated as multiple choices under each question. Respondents should select one option for each question**
- **Third section includes information about the total annual demand for procured items. In this section, respondents may provide three types of information related to demand [historical (real data for 2012), historical (rough estimates of respondents) and historical (previosus 5 years (except 2012))] .**
- **Fourth section relates to ranking of suppliers. In this section, please mark a "X" in the box against the most appropriate option.**
- **Fifth section involves capability-based risks. In this section, Linguistic Variables (extremely important, very important, important, moderately important, and equally important) are represented as multiple choices under each question. Respondents should select one option for each question**
- **Sixth section includes performance-based risks. In this section, three values (pessimistic, probabilistic, optimistic), should be used to answer for each supplier.**

INSTRUCTION FOR TABLES

Table 1 shows the availabity of criteria. If you do not use any of the criteria listed in column 1, you may not answer related questions given in column 2. You may skip these questions. Table 2 represents descriptions of Capability-based Risks and Table 3 represents description of Performance-based Risks.

Table 1: Availability of Criteria

Criteria	Related Questions	Data Availability (Yes/No)
Total Cost	4,5,6	
Late Delivery Percentage	4,7,8,38	
Defect Percentage	5,7,9,39	
Historical (real) Demand	10*	
Historical (estimates) Demand	11*	
Historical (previous 5 years) Demand	12*	
Current Order Allocation	13	
Financial Positon of Supplier	14,15,16,17,18,29	
Volume Flexibility	14,19,20,21,22,30	
Technological Capability	15,19,23,24,25,31	
Reputation	16,20,23,26,27,32	
Compliance with Sectoral Price	17,21,24,26,28,33	
Communication Issues	18,22,25,27,28,34	
Purchasing Price	35	
Transportation Cost	36	
Ordering Cost	37	
Capacity of Suppliers	40	
Capacity of Trucks	41	
Availability of Trucks	42	

*If Respondents do not give historical (real) demand, they can provide estimates about demand (Question 5). This question just includes the opinion of respondents. Additionally, respondents may provide historical demand for evaluation of demand for last the 5 years (except 2012).

Table 2: Descriptions of Capability-based Risks

Criteria	Description
Financial Position of Supplier	The status of supplier in the market in terms of its assets and liabilities
Volume Flexibility	The ability of a supplier's manufacturing process to handle large variations in volume without significant changes in time and facility requirement
Technological Capability	Supplier's ability to adopt high-end technologies in its manufacturing processes
Reputation	Supplier's relative position (against competitors) in the industry including product leadership and brand image
Compliance with Sectoral Price	The supplier's purchasing price of item not being over the market average
Communication Issues	Lack of commnunication between manufacturer and supplier in relation to information exchange about the procured items

Table 3: Descriptions of Performance-based Risks

Criteria	Description
Total Cost	The sum of purchasing price, transportation cost and ordering cost
Defect Percentage	The percentage of defective items received
Late Delivery Percentage	The percentage of items received later than promised delivery date

SECTION I - GENERAL INFORMATION ABOUT THE PROCUREMENT PROCESS OF THE COMPANY

1- Which item is the most important for your company in the supplier selection process?

2-How many suppliers do you work with for this item?

3- Are you currently using any software tool(s) to evaluate suppliers for this item?

SECTION II - COMPARISON OF PERFORMANCE-BASED RISKS

QUESTIONS	CHOICES				
	Extremely Important	Very Important	Important	Moderately Important	Equally Important
4- How Important is "Total Cost" for you when it is compared with "Late Delivery Percentage"?	☐	☐	☐	☐	☐
5- How Important is "Total Cost" for you when it is compared with "Defect Percentage"?	☐	☐	☐	☐	☐
6- How Important is "Total Cost" for you when it is compared with "Capability-based Risks"?	☐	☐	☐	☐	☐
7- How Important is "Late Delivery Percentage" for you when it is compared with "Defect Percentage"?	☐	☐	☐	☐	☐
8- How Important is "Late Delivery Percentage" for you when it is compared with "Capability-based Risks"?	☐	☐	☐	☐	☐
9- How Important is "Defect Percentage" for you when it is compared with "Capability-based Risks"?	☐	☐	☐	☐	☐

SECTION III - IDENTIFY DEMAND

10- What was the annual demand for this item for 2012?

11- If you did not reply to question 4, what was the estimated annual demand (rough estimates) for this item for 2012?

Please, write three values (pessimistic value, probabilistic value and optimistic value)

	Pessimistic Value	Probabilistic Value	Optimistic Value
Annual Demand			

12- What was the annual demand of this item for the last 5 previous year (except 2012)?

Year	Demand of Item
2007	
2008	
2009	
2010	
2011	

13- What was order quantity for this item for each supplier for 2012?

Suppliers	Order Quantity
Supplier 1	
Supplier 2	
Supplier 3	
Supplier 4	
Supplier 5	
Supplier 6	
Supplier 7	

SECTION IV - COMPARISON OF CAPABILITY-BASED RISKS

QUESTIONS	CHOICES				
	Extremely Important	Very Important	Important	Moderately Important	Equally Important
14- How Important is "Financial Position of Supplier" for you when it is compared with "Volume Flexibility"?	☐	☐	☐	☐	☐
15- How Important is "Financial Position of Supplier" for you when it is compared with "Technological Capability"?	☐	☐	☐	☐	☐
16- How Important is "Financial Position of Supplier" for you when it is compared with "Reputation"?	☐	☐	☐	☐	☐
17- How Important is "Financial Position of Supplier" for you when it is compared with "Compliance with Sectoral Price?	☐	☐	☐	☐	☐
18- How Important is "Financial Position of Supplier" for you when it is compared with "Communication Issues"?	☐	☐	☐	☐	☐
19- How Important is "Volume Flexibility" for you when it is compared with "Technological Capability"?	☐	☐	☐	☐	☐
20- How Important is "Volume Flexibility" for you when it is compared with "Reputation"?	☐	☐	☐	☐	☐
21- How Important is "Volume Flexibility" for you when it is compared with "Compliance with Price"?	☐	☐	☐	☐	☐
22- How Important is "Volume Flexibility" for you when it is compared with "Communication Issues"?	☐	☐	☐	☐	☐
23- How Important is "Technological Capability" for you when it is compared with "Reputation"?	☐	☐	☐	☐	☐
24- How Important is "Technological Capability" for you when it is compared with "Compliance with Sectoral Price"?	☐	☐	☐	☐	☐
25- How Important is "Technological Capability" for you when it is compared with "Communication Issues"?	☐	☐	☐	☐	☐
26- How Important is "Reputation" for you when it is compared with "Compliance with Sectoral Price"?	☐	☐	☐	☐	☐
27- How Important is "Reputation" for you when it is compared with "Communication Issues"?	☐	☐	☐	☐	☐
28- How Important is "Compliance with Sectoral Price" for you when it is compared with "Communication Issues"?	☐	☐	☐	☐	☐

SECTION V - RANKING OF SUPPLIERS (CAPABILITY-BASED RISKS)

29- Please, evaluate each supplier with regards to their Financial Position (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

30- Please, evaluate each supplier with regards to their Volume Flexibility (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

31- Please, evaluate each supplier with regards to their Technological Capability (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

32- Please, evaluate each supplier with regards to their Reputation (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

33- Please, evaluate each supplier with regards to their Compliance with Sectoral Price (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

34- Please, evaluate each supplier with regards to their Communication Issues (mark 'X' in the appropriate cell)

Suppliers	Very High	High	Medium	Low	Very Low
Supplier 1	☐	☐	☐	☐	☐
Supplier 2	☐	☐	☐	☐	☐
Supplier 3	☐	☐	☐	☐	☐
Supplier 4	☐	☐	☐	☐	☐
Supplier 5	☐	☐	☐	☐	☐
Supplier 6	☐	☐	☐	☐	☐
Supplier 7	☐	☐	☐	☐	☐

SECTION VI - RANKING OF SUPPLIERS (PERFORMANCE-BASED RISKS)

35- What was the purchasing price of this item from each supplier for 2012?
Please, write three values (pessimistic value, probabilistic value and optimistic value)

Suppliers	Pessimistic Value	Probabilistic Value	Optimistic Value
Supplier 1			
Supplier 2			
Supplier 3			
Supplier 4			
Supplier 5			
Supplier 6			
Supplier 7			

36- What was the transportation cost per truck from each supplier for 2012?
Please, write three values (pessimistic value, probabilistic value and optimistic value)

Suppliers and Trucks	Pessimistic Value	Probabilistic Value	Optimistic Value
Supplier 1-Truck 1			
Supplier 1-Truck 2			
Supplier 1-Truck 3			
Supplier 1-Truck 4			
Supplier 2-Truck 1			
Supplier 2-Truck 2			
Supplier 2-Truck 3			
Supplier 2-Truck 4			
Supplier 3-Truck 1			
Supplier 3-Truck 2			
Supplier 3-Truck 3			
Supplier 3-Truck 4			
Supplier 4-Truck 1			
Supplier 4-Truck 2			
Supplier 4-Truck 3			
Supplier 4-Truck 4			
Supplier 5-Truck 1			
Supplier 5-Truck 2			
Supplier 5-Truck 3			
Supplier 5-Truck 4			
Supplier 6-Truck 1			
Supplier 6-Truck 2			
Supplier 6-Truck 3			
Supplier 6-Truck 4			
Supplier 7-Truck 1			
Supplier 7-Truck 2			
Supplier 7-Truck 3			
Supplier 7-Truck 4			

37- What was the most probabilistic value of ordering cost per truck from each supplier for 2012?

Suppliers and Trucks	Probabilistic Value
Supplier 1-Truck 1	
Supplier 1-Truck 2	
Supplier 1-Truck 3	
Supplier 1-Truck 4	
Supplier 2-Truck 1	
Supplier 2-Truck 2	
Supplier 2-Truck 3	
Supplier 2-Truck 4	
Supplier 3-Truck 1	
Supplier 3-Truck 2	
Supplier 3-Truck 3	
Supplier 3-Truck 4	
Supplier 4-Truck 1	
Supplier 4-Truck 2	
Supplier 4-Truck 3	
Supplier 4-Truck 4	
Supplier 5-Truck 1	
Supplier 5-Truck 2	
Supplier 5-Truck 3	
Supplier 5-Truck 4	
Supplier 6-Truck 1	
Supplier 6-Truck 2	
Supplier 6-Truck 3	
Supplier 6-Truck 4	
Supplier 7-Truck 1	
Supplier 7-Truck 2	
Supplier 7-Truck 3	
Supplier 7-Truck 4	

38- What percentage of items did you receive from a supplier late for 2012 ?
Please, write three values (pessimistic value, probabilistic value and optimistic value)

Suppliers	Pessimistic Value	Probabilistic Value	Optimistic Value
Supplier 1			
Supplier 2			
Supplier 3			
Supplier 4			
Supplier 5			
Supplier 6			
Supplier 7			

39- What percentage of defective items did you receive from a supplier for 2012?
Please, write three values (pessimistic value, probabilistic value and optimistic value)

Suppliers	Pessimistic Value	Probabilistic Value	Optimistic Value
Supplier 1			
Supplier 2			
Supplier 3			
Supplier 4			
Supplier 5			
Supplier 6			
Supplier 7			

40- In your opinion, what would be the estimated production capacity for each supplier for this item for 2012? Please, write three values (pessimistic value, probabilistic value and optimistic value)

Suppliers	Pessimistic Value	Probabilistic Value	Optimistic Value
Supplier 1			
Supplier 2			
Supplier 3			
Supplier 4			
Supplier 5			
Supplier 6			
Supplier 7			

41- What are the capacities of these trucks for this item?

Trucks	Capacity
Truck 1	
Truck 2	
Truck 3	
Truck 4	

42- What was the maximum number of trucks for each supplier for 2012?

	Suppliers						
Trucks	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Supplier 7
Truck 1							
Truck 2							
Truck 3							
Truck 4							

Correction Note for Supplier Performance Questionnaire

In question 11, question 4 has been wrongly written instead of question 10. However, participated managers directly have answered question 10, so there was not any requirement for question 11.

APPENDIX C: FEASIBILITY QUESTIONNAIRE

THE QUESTIONNAIRE FOR EVALUATING THE FEASIBILITY OF THE PROPOSED MODEL

COMPANY CODE NAME:

POSITON OF RESPONDENT:

DATE:

INTRODUCTIONS

This questionnaire is intended to be completed by selected management staff of Turkish textile companies to evaluate the feasibility of the proposed model and the suitability the supplier selection criteria used in the proposed model.

INSTRUCTIONS

You may choose not to answer any or all of the questions. If you wish not to answer any of the questions please skip that question and proceed to the next question. Please circle the number for each question.

This questionnaire consists of two sections.

-First section includes evaluation of supplier selection criteria and objectives.

-Second section includes comparison of model results with against current organisational practices.

SECTION I - SUITABILITY OF CRITERIA AND OBJECTIVES

1- You have been shown criteria [shown in Appendix A] used in the proposed model for supplier selection To what extent do you believe that these criteria are suitable for consideration in the supplier selection process in practice?

0	1	2	3	4	5	6	7	8	9	10

Not at all Partially Completely

2- You have been shown the objectives [shown in Appendix A] of the proposed model for supplier selection.To what extent do youbelieve that these objectives are suitable for consideration in the supplier selection process in practice?

0	1	2	3	4	5	6	7	8	9	10

Not at all Partially Completely

SECTION II - SUITABILITY OF ORDER ALLOCATION AND RESULTS OF THE PROPOSED MODEL

3- You have been shown order allocation to suppliers. To what extent do you believe that this order allocation can be feasible for practice?

0	1	2	3	4	5	6	7	8	9	10

Not at all Partially Completely

4- You have been shown the selected suppliers and results including cost, late delivery rate, defect rate. If you selected these suppliers, would you have similar results in practice?

0	1	2	3	4	5	6	7	8	9	10

Not at all Partially Completely

APPENDIX D: OBTAINED DATA FROM COMPANIES

Table 1D: Linguistic Weights of Qualitative Criteria for Company A

Manager	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Financial Position	-	EI	EI	I	EI	MI
	Volume Flexibility		-	EI	I	EI	MI
	Technological Capability			-	I	EI	MI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.							

Table 2D: Linguistic Scores of Suppliers under Criteria for Company A

Manager	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Supplier 1	H	VH	VH	M	H	M
	Supplier 2	H	H	VH	H	H	M
	Supplier 3	H	H	H	H	H	M
	Supplier 4	H	H	M	M	H	H
Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.							

Table 3D: Linguistic Weights of Objective Functions for Company A

Manager	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Factory Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	EI	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.					

Table 4D: Linguistic Weights of Qualitative Criteria of Company B

Manager	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Purchasing Manager	Financial Position	-	VI	VI	VI	VI	VI
	Volume Flexibility		-	VI	I	MI	I
	Technological Capability			-	I	EI	I
	Reputation				-	EI	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 5D: Linguistic Scores of Suppliers under Criteria for Company B

Manager	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Purchasing Manager	Supplier 1	H	VH	H	M	H	VL
	Supplier 2	H	VH	H	H	H	VL
	Supplier 3	M	H	H	M	H	VL
	Supplier 4	M	H	M	M	H	VL
	Supplier 5	H	VH	H	M	H	VL

Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.

Table 6D: Linguistic Weights of Objective Functions for Company B

Manager	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Purchasing Manager	Total Cost	-	I	I	EXI
	Late Delivery Percentage		-	I	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 7D: Linguistic Weights of Qualitative Criteria for Company C

Managers	**Criteria** / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Factory Manager	Financial Position	-	I	I	VI	VI	VI
	Volume Flexibility		-	VI	I	VI	I
	Technological Capability			-	VI	I	I
	Reputation				-	VI	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Financial Position	-	EXI	VI	VI	VI	EXI
	Volume Flexibility		-	VI	VI	I	I
	Technological Capability			-	I	I	I
	Reputation				-	I	VI
	Compliance with Sectoral Price					-	I
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Financial Position	-	EXI	EXI	I	VI	VI
	Volume Flexibility		-	I	VI	I	VI
	Technological Capability			-	VI	MI	VI
	Reputation				-	MI	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Financial Position	-	I	VI	VI	EI	VI
	Volume Flexibility		-	I	VI	EI	VI
	Technological Capability			-	I	EI	VI
	Reputation				-	EI	VI
	Compliance with Sectoral Price					-	VI
	Communication Issues						-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.							

Table 8D: Linguistic Scores of Suppliers under Criteria for Company C

Managers	**Criteria / Suppliers**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Factory Manager	Supplier 1	VH	VH	H	H	H	L
	Supplier 2	M	VH	M	M	M	L
	Supplier 3	H	VH	M	H	H	L
	Supplier 4	M	VH	M	M	H	M
	Supplier 5	M	VH	M	H	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Supplier 1	H	H	H	M	H	M
	Supplier 2	M	H	M	VH	M	L
	Supplier 3	H	H	H	H	H	L
	Supplier 4	H	H	M	H	H	M
	Supplier 5	H	H	M	H	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Supplier 1	H	M	H	H	H	L
	Supplier 2	M	M	H	M	M	L
	Supplier 3	M	M	H	H	H	VL
	Supplier 4	M	M	M	L	H	VL
	Supplier 5	M	M	H	M	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Supplier 1	VH	H	VH	M	L	VL
	Supplier 2	M	H	M	M	L	VL
	Supplier 3	M	H	H	H	L	VL
	Supplier 4	H	H	M	H	L	VL
	Supplier 5	H	H	H	H	M	VL
Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.							

Table 9D: Linguistic Weights of Objective Functions for Company C

Managers	**Objective Functions** / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Factory Manager	Total Cost	-	VI	VI	EXI
	Late Delivery Percentage		-	I	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
	Objective Functions / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Financial Manager	Total Cost	-	I	VI	I
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Planning Manager	Total Cost	-	I	VI	VI
	Late Delivery Percentage		-	VI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Quality Manager	Total Cost	-	I	VI	EXI
	Late Delivery Percentage		-	VI	EXI
	Defect Percentage			-	EXI
	Qualitative Aspects				-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.					

Table 10D: Linguistic Weights of Qualitative Criteria for Company D

Managers	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Financial Position	-	I	I	I	I	I
	Volume Flexibility		-	I	I	I	I
	Technological Capability			-	MI	MI	I
	Reputation				-	MI	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Financial Position	-	I	I	MI	I	MI
	Volume Flexibility		-	I	I	I	I
	Technological Capability			-	MI	EI	MI
	Reputation				-	MI	MI
	Compliance with Sectoral Price					-	I
	Communication Issues						-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 11D: Linguistic Scores of Suppliers under Criteria for Company D

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Supplier 1	VH	VH	VH	H	M	L
	Supplier 2	H	VH	VH	H	M	L
	Supplier 3	H	H	VH	H	H	L
	Supplier 4	H	H	VH	H	H	L
	Supplier 5	VH	VH	M	H	M	L
	Supplier 6	M	H	M	H	M	L
	Supplier 7	M	H	M	M	M	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Supplier 1	VH	VH	VH	M	H	M
	Supplier 2	H	H	H	M	H	L
	Supplier 3	H	H	H	H	H	L
	Supplier 4	H	VH	H	M	H	L
	Supplier 5	H	VH	H	H	H	L
	Supplier 6	M	H	M	VH	H	L
	Supplier 7	M	H	M	M	H	L

Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.

Table 12D: Linguistic Weights of Objective Functions for Company D

Managers	**Objective Functions** / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Factory Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / **Objective Functions**	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Purchasing Manager	Total Cost	-	MI	VI	VI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	VI
	Qualitative Aspects				-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.					

Table 13D: Linguistic Weights of Qualitative Criteria for Company E

Managers	Criteria \ Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Operational Director	Financial Position	-	VI	VI	I	MI	EI
	Volume Flexibility		-	VI	I	MI	EI
	Technological Capability			-	I	EI	EI
	Reputation				-	EI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
CFO	Financial Position	-	MI	MI	MI	MI	MI
	Volume Flexibility		-	MI	MI	I	EI
	Technological Capability			-	MI	I	EI
	Reputation				-	MI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
COO	Financial Position	-	I	I	MI	MI	MI
	Volume Flexibility		-	I	MI	MI	MI
	Technological Capability			-	I	MI	EI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Financial Position	-	VI	VI	EXI	VI	I
	Volume Flexibility		-	EI	VI	VI	I
	Technological Capability			-	VI	VI	I
	Reputation				-	VI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 14D: Linguistic Scores of Suppliers under Criteria for Company E

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Operational Director	Supplier 1	H	VH	VH	M	M	M
	Supplier 2	M	VH	VH	H	M	M
	Supplier 3	M	VH	H	H	M	M
	Supplier 4	M	VH	M	M	M	H
	Supplier 5	M	VH	M	M	M	L
	Supplier 6	M	M	M	M	VH	L
	Supplier 7	M	M	M	M	M	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
CFO	Supplier 1	H	VH	H	H	H	L
	Supplier 2	H	VH	H	H	H	M
	Supplier 3	H	VH	VH	M	M	M
	Supplier 4	H	H	H	M	L	M
	Supplier 5	H	H	M	H	M	L
	Supplier 6	H	H	H	VH	VH	M
	Supplier 7	H	H	M	M	M	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
COO	Supplier 1	VH	VH	VH	H	M	L
	Supplier 2	H	H	H	H	M	L
	Supplier 3	H	H	H	H	M	L
	Supplier 4	H	VH	M	M	L	H
	Supplier 5	H	H	H	M	M	L
	Supplier 6	H	H	H	H	H	L
	Supplier 7	H	VH	M	M	M	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Supplier 1	H	VH	VH	M	L	M
	Supplier 2	M	VH	VH	H	L	M
	Supplier 3	H	M	H	M	L	L
	Supplier 4	M	VH	M	M	L	M
	Supplier 5	M	VH	H	H	L	M
	Supplier 6	H	M	M	H	VH	L
	Supplier 7	H	M	M	M	L	L

Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.

Table 15D: Linguistic Weights of Objective Functions for Company E

Managers	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Operational Director	Total Cost	-	I	I	VI
	Late Delivery Percentage		-	I	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
CFO	Total Cost	-	MI	I	EXI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
COO	Total Cost	-	EI	I	VI
	Late Delivery Percentage		-	VI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Planning Manager	Total Cost	-	EI	VI	EXI
	Late Delivery Percentage		-	EXI	EXI
	Defect Percentage			-	EXI
	Qualitative Aspects				-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 16D: Linguistic Weights of Qualitative Criteria for Company F

Managers	Criteria \ Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Financial Position	-	I	MI	MI	MI	MI
	Volume Flexibility		-	MI	MI	MI	MI
	Technological Capability			-	MI	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Financial Position	-	I	MI	I	I	I
	Volume Flexibility		-	MI	I	I	MI
	Technological Capability			-	VI	VI	I
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Financial Position	-	VI	VI	VI	VI	MI
	Volume Flexibility		-	I	I	MI	MI
	Technological Capability			-	I	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Financial Position	-	I	VI	I	I	MI
	Volume Flexibility		-	I	I	I	MI
	Technological Capability			-	I	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria \ Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
HRM	Financial Position	-	I	VI	VI	VI	EI
	Volume Flexibility		-	VI	VI	VI	EI
	Technological Capability			-	VI	I	EI

	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
	Reputation				-	I	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
CRM	Financial Position	-	MI	VI	EI	EI	EI
	Volume Flexibility		-	MI	EI	EI	EI
	Technological Capability			-	EI	EI	EI
	Reputation				-	EI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 17D: Linguistic Scores of Suppliers under Criteria for Company F

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Supplier 1	VH	VH	VH	VH	H	M
	Supplier 2	VH	H	H	H	L	M
	Supplier 3	H	H	H	H	L	M
	Supplier 4	H	H	H	H	L	M
	Supplier 5	VH	H	H	VH	H	M
	Supplier 6	VH	H	VH	VH	H	L
	Supplier 7	H	H	H	H	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Supplier 1	VH	VH	VH	VH	H	M
	Supplier 2	VH	VH	H	H	L	M
	Supplier 3	VH	VH	H	H	L	M
	Supplier 4	H	VH	H	H	L	M
	Supplier 5	H	VH	H	VH	H	L
	Supplier 6	H	VH	H	VH	H	L
	Supplier 7	H	VH	H	VH	H	L

	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Quality Manager	Supplier 1	VH	H	H	VH	VH	H
	Supplier 2	VH	H	H	H	H	M
	Supplier 3	VH	H	H	H	H	H
	Supplier 4	H	H	H	H	H	H
	Supplier 5	VH	H	H	H	VH	M
	Supplier 6	VH	H	VH	H	VH	M
	Supplier 7	VH	H	H	VH	VH	M
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Supplier 1	VH	VH	VH	VH	H	M
	Supplier 2	VH	H	H	H	L	M
	Supplier 3	VH	H	H	H	L	H
	Supplier 4	VH	H	H	VH	L	M
	Supplier 5	VH	H	VH	VH	H	M
	Supplier 6	H	H	VH	VH	H	L
	Supplier 7	H	H	VH	VH	H	M
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
HRM	Supplier 1	VH	VH	VH	VH	H	M
	Supplier 2	VH	VH	H	H	L	M
	Supplier 3	VH	VH	H	VH	L	M
	Supplier 4	H	VH	VH	VH	L	M
	Supplier 5	VH	H	VH	H	H	L
	Supplier 6	VH	H	VH	H	H	L
	Supplier 7	VH	H	VH	H	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
CRM	Supplier 1	VH	VH	VH	VH	VH	H
	Supplier 2	VH	H	H	H	H	H
	Supplier 3	VH	H	H	H	H	H
	Supplier 4	VH	H	VH	H	H	H
	Supplier 5	VH	H	VH	VH	VH	L
	Supplier 6	VH	H	H	H	VH	L
	Supplier 7	VH	H	VH	VH	VH	L

Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.

Table 18D: Linguistic Weights of Objective Functions for Company F

Managers	Objective Functions (columns) / Objective Functions (rows)	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Factory Manager	Total Cost	-	MI	I	VI
	Late Delivery Percentage		-	MI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Planning Manager	Total Cost	-	EI	VI	VI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Quality Manager	Total Cost	-	I	I	VI
	Late Delivery Percentage		-	I	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Purchasing Manager	Total Cost	-	MI	I	VI
	Late Delivery Percentage		-	MI	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
HRM	Total Cost	-	I	I	I
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I

	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
CRM	Total Cost	-	MI	I	I
	Late Delivery Percentage		-	MI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.					

Table 19D: Linguistic Weights of Qualitative Criteria for Company G

Managers	**Criteria / Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Factory Manager	Financial Position	-	VI	VI	I	MI	MI
	Volume Flexibility		-	VI	I	MI	MI
	Technological Capability			-	I	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Financial Position	-	VI	VI	VI	VI	EI
	Volume Flexibility		-	VI	VI	EI	EI
	Technological Capability			-	VI	EI	EI
	Reputation				-	EI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Financial Position	-	EI	EI	EI	MI	MI
	Volume Flexibility		-	VI	EI	MI	MI
	Technological Capability			-	EI	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.							

Table 20D: Linguistic Scores of Suppliers under Criteria for Company G

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Supplier 1	H	H	H	M	M	M
	Supplier 2	H	H	H	H	M	L
	Supplier 3	H	H	VH	H	M	L
	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Financial Manager	Supplier 1	H	H	H	M	M	M
	Supplier 2	H	M	H	M	H	M
	Supplier 3	H	H	VH	H	H	M
	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Quality Manager	Supplier 1	H	VH	VH	H	M	M
	Supplier 2	M	VH	H	M	M	L
	Supplier 3	H	VH	VH	H	M	L

Table 21D: Linguistic Weights of Objective Functions for Company G

Managers	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Factory Manager	Total Cost	-	I	I	VI
	Late Delivery Percentage		-	I	VI
	Defect Percentage			-	VI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Financial Manager	Total Cost	-	I	I	I
	Late Delivery Percentage		-	EI	EI
	Defect Percentage			-	I
	Qualitative Aspects				-

	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Quality Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-

Table 22D: Linguistic Weights of Qualitative Criteria for Company H

Managers	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Financial Position	-	VI	VI	I	VI	I
	Volume Flexibility		-	VI	I	VI	EI
	Technological Capability			-	I	VI	EI
	Reputation				-	VI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Financial Position	-	VI	VI	VI	I	VI
	Volume Flexibility		-	VI	VI	I	VI
	Technological Capability			-	VI	I	I
	Reputation				-	EI	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-
	Criteria / Criteria	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Financial Position	-	VI	VI	I	I	I
	Volume Flexibility		-	VI	I	I	I
	Technological Capability			-	I	I	I
	Reputation				-	I	I
	Compliance with Sectoral Price					-	I
	Communication Issues						-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.							

Table 23D: Linguistic Scores of Suppliers under Criteria for Company H

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Factory Manager	Supplier 1	H	VH	VH	H	M	M
	Supplier 2	M	H	VH	H	M	M
	Supplier 3	M	H	H	M	M	M
	Supplier 4	H	H	H	H	M	M
	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Financial Manager	Supplier 1	H	VH	VH	H	H	M
	Supplier 2	H	H	VH	H	H	M
	Supplier 3	H	H	L	M	H	H
	Supplier 4	H	H	H	H	H	M
	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Quality Manager	Supplier 1	H	VH	H	H	H	M
	Supplier 2	H	H	H	H	H	M
	Supplier 3	H	H	M	M	M	H
	Supplier 4	H	H	H	VH	H	M

Table 24D: Linguistic Weights of Objective Functions for Company H

Managers	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Factory Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	EI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Financial Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	I	I
	Defect Percentage			-	I
	Qualitative Aspects				-

	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Quality Manager	Total Cost	-	VI	VI	VI
	Late Delivery Percentage		-	EI	VI
	Defect Percentage			-	I
	Qualitative Aspects				-

APPENDIX E: FUZZY STOCHASTIC MODEL

Equation 1 indicates general form of fuzzy stochastic goal where $\widetilde{e}_{Mr}$ is a fuzzy coefficient, x_M is a non-negative variable, b_r is independent random variable with known distribution, ($\lesssim and \gtrsim$) are fuzziness of ($\leq and \geq$)and β_r is tolerance value.

$$\Pr(\sum_{M=1}^{C} \widetilde{e}_{Mr} \times x_M \lesssim b_r) \gtrsim \beta_r \qquad r = 1,2,3, \ldots . R \tag{1}$$

For solving fuzzy stochastic goal programming, first fuzzy coefficients are converted into crisp coefficients by expected value method. Heilpern (1992) calculated Expected Interval (EI) of a fuzzy number $\widetilde{e}$ using following equation:

$$EI(\widetilde{e}) = [E_1^e, E_2^e] = \left[\int_0^1 f_e^{-1}(h)\ dh, \int_0^1 g_e^{-1}(h)\right] \tag{2}$$

According to Jiménez et al. (2007) , Expected Value (EV) of fuzzy number $\widetilde{e}$, is the half point of its Expected Interval (EI).Therefore, Expected Value (EV) can be calculated using following equation:

$$EV(\widetilde{e}) = \frac{E_1^e + E_2^e}{2} \tag{3}$$

Expected Value (EV) can be calculated for triangular numbers (Torabi and Amiri, 2012) as:

$$EV(\widetilde{e}) = \frac{1}{4} \times (l(\tilde{e}) + 2 \times m(\tilde{e}) + u(\tilde{e})) \tag{4}$$

In Equation 4, $l(\tilde{e})$, $m(\tilde{e})$ and $u(\tilde{e})$ are the lower value, the medium value and upper value of $\tilde{e}$ respectively. After converting fuzzy coefficients into crisp value (expected value) by Eq. 4, new fuzzy stochastic goal can be written as:

$$\Pr(\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \lesssim b_r) \gtrsim \beta_r \qquad r = 1,2,3, \ldots . R \tag{5}$$

This fuzzy stochastic goal can be written as constraints with respect to the satisfaction of the decision maker (Iskander, 2004). The decision maker is fully satisfied:

$$\Pr(\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le b_r) \ge \beta_r \qquad r = 1,2,3, \ldots .R \tag{6}$$

If the decision maker is almost satisfied or not satisfied, decision maker determines slack values (δ_r and c_{Mr}) to convert fuzzy stochastic goal (Eq.5) into crisp constraints. If the decision maker is almost satisfied fuzzy stochastic goal can be written as:

$$\delta_r \le \Pr(\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le b_r) \le \beta_r \qquad r = 1,2,3, \ldots .R \tag{7}$$

$$\beta_r \le \Pr(\sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \le b_r) \qquad r = 1,2,3, \ldots .R \tag{8}$$

If the decision maker is not satisfied fuzzy stochastic goal can be written as:

$$\Pr(\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le b_r) \le \delta_r \qquad r = 1,2,3, \ldots .R \tag{9}$$

$$\Pr(\sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \le b_r) \le \beta_r \qquad r = 1,2,3, \ldots .R \tag{10}$$

These constraints (equations 6-10) are converted into deterministic equals

$$\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le F_r^{-1}(1-\beta_r), \qquad r = 1,2,3, \ldots .R \tag{11}$$

$$F_r^{-1}(1-\beta_r) \le \sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le F_r^{-1}(1-\delta_r) \qquad r = 1,2,3, \ldots .R \qquad \text{and}$$

$$\sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \le F_r^{-1}(1-\beta_r), \qquad r = 1,2,3, \ldots .R \tag{12}$$

$$\sum_{M=1}^{C} EV(e_{Mr}) \times x_M \ge F_r^{-1}(1-\delta_r), \qquad r = 1,2,3, \ldots .R \qquad \text{or}$$

$$F_r^{-1}(1-\beta_r) \le \sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M, \qquad r = 1,2,3, \ldots .R \tag{13}$$

Equation 14 represents fuzzy membership (μ_r) of equations 11-13 where g_r (linear) and nh_r (non-linear) membership functions.

$$\mu_r = \begin{cases} 1 & \text{If } \sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le F_r^{-1}(1-\beta_r) \\ \min(g_r, nh_r) & \text{If } \sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \le F_r^{-1}(1-\beta_r) \le \sum_{M=1}^{C} EV(e_{Mr}) \times x_M \le F_r^{-1}(1-\delta_r) \\ 0 & \text{If } F_r^{-1}(1-\beta_r) \le \sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \text{ or } \sum_{M=1}^{C} EV(e_{Mr}) \times x_M \ge F_r^{-1}(1-\delta_r) \end{cases} \tag{14}$$

Fuzzy membership functions (g_r and nh_r) of above function can be written as:

$$g_r = \left(F_r^{-1}(1-\delta_r) - \sum_{M=1}^{C} EV(e_{Mr}) \times x_M \right) \Big/ \left(F_r^{-1}(1-\delta_r) - F_r^{-1}(1-\beta_r) \right),$$

$$r = 1,2,3, \ldots .R \tag{15}$$

$$nh_r = \left(F_r^{-1}(1-\beta_r) - \sum_{M=1}^{C} (EV(e_{Mr}) - c_{Mr}) \times x_M \right) \Big/ \sum_{M=1}^{C} c_{Mr} \times x_M,$$

$$r = 1,2,3, \dots .R \qquad (16)$$

Apart from fuzzy stochastic goal programming, fuzzy goal programming is used to maximise total score in model in chapter 5. Fuzzy membership of fuzzy goal (Jamalnia and Soukhakian, 2009) can be written as:

$$\mu_l\big(Z_l(x)\big) = \begin{cases} 1, & G_l(x) \geq g_l \\ \frac{(G_l(x) - LW_l)}{(g_l - LW_l)}, & LW_l \leq G_l(x) \leq g_l \,, \; l = 1,2 \dots .L \\ 0, & G_l(x) \leq LW_l \end{cases} \qquad (17)$$

In equation 17, LW_l is lower bound for l^{th} fuzzy goal ($G_l(x)$) and g_l is the aspiration level for l^{th} goal.

APPENDIX F: FUZZY AND STOCHASTIC DATA

Table 1F: Linguistic Weights of Qualitative Criteria for Quantity Discount Problem

Managers	**Criteria** / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Financial Position	-	I	MI	I	EI	EI
	Volume Flexibility		-	MI	I	EI	MI
	Technological Capability			-	MI	EI	MI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Financial Position	-	MI	MI	I	MI	I
	Volume Flexibility		-	EI	EI	I	I
	Technological Capability			-	EI	I	MI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Financial Position	-	I	MI	MI	MI	MI
	Volume Flexibility		-	EI	MI	MI	MI
	Technological Capability			-	MI	EI	MI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Financial Position	-	EI	EI	EI	MI	MI
	Volume Flexibility		-	EI	I	MI	MI
	Technological Capability			-	I	I	EI
	Reputation				-	I	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 2F: Linguistic Scores of Suppliers under Criteria for Quantity Discount Problem

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Purchasing Manager	Supplier 1	H	H	H	H	L	M
	Supplier 2	VH	H	H	H	M	M
	Supplier 3	H	VH	H	M	M	M
	Supplier 4	H	H	VH	H	L	M
	Supplier 5	H	H	M	H	L	VL
	Supplier 6	H	H	VH	VH	L	VL
	Supplier 7	VH	H	VH	VH	L	VL
	Supplier 8	H	H	H	H	L	VL
	Supplier 9	H	H	H	H	L	VL
	Supplier 10	H	H	H	M	L	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Supplier 1	H	H	H	VH	H	L
	Supplier 2	H	H	VH	H	L	L
	Supplier 3	H	H	H	H	L	L
	Supplier 4	H	H	H	H	L	L
	Supplier 5	H	H	H	VH	H	L
	Supplier 6	H	H	M	VH	H	L
	Supplier 7	VH	VH	H	VH	H	L
	Supplier 8	H	H	H	VH	H	L
	Supplier 9	H	H	H	VH	H	L
	Supplier 10	H	H	H	H	H	L
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Supplier 1	H	H	H	VH	H	H
	Supplier 2	VH	H	H	H	L	M
	Supplier 3	H	H	M	H	L	M
	Supplier 4	H	H	H	H	H	M
	Supplier 5	H	H	M	H	H	M
	Supplier 6	M	H	H	M	H	M
	Supplier 7	VH	H	H	VH	H	M
	Supplier 8	H	H	M	H	H	L
	Supplier 9	VH	H	M	H	H	L
	Supplier 10	M	M	L	H	H	L

	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Planning Manager	Supplier 1	M	H	H	H	H	M
	Supplier 2	VH	H	H	H	L	M
	Supplier 3	H	H	H	H	L	M
	Supplier 4	H	H	H	H	L	M
	Supplier 5	H	M	H	M	H	L
	Supplier 6	M	H	M	VH	H	L
	Supplier 7	VH	VH	M	VH	H	VL
	Supplier 8	M	VH	H	H	H	L
	Supplier 9	H	H	H	H	M	L
	Supplier 10	H	H	M	H	M	L
Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.							

Table 3F: Linguistic Weights of Objective Functions for Quantity Discount Problem

Managers	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Purchasing Manager	Total Cost	-	MI	I	I
	Late Delivery Percentage		-	EI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Financial Manager	Total Cost	-	MI	MI	I
	Late Delivery Percentage		-	MI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Planning Manager	Total Cost	-	MI	MI	EI
	Late Delivery Percentage		-	MI	EI
	Defect Percentage			-	EI

	Qualitative Aspects				-
	Objective Functions \ Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Quality Manager	Total Cost	-	MI	EI	I
	Late Delivery Percentage		-	MI	I
	Defect Percentage			-	EI
	Qualitative Aspects				-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.					

Table 4F: Quantity Levels, Purchasing Price and Capacity of Suppliers

Suppliers	**Quantity Level**	**Purchasing Price ($)**	**Slack Values**	**Capacity**
Supplier 5	$QL < 300$;	(3,3.5,4)	0.5	N(2400,100)
	$300 \leq QL < 800$;	(3.1,3.2,3.3)	0.5	
	$800 \leq QL$	(2,3,4)	0.5	
Supplier 6	$QL < 450$;	(2.75,3.75,4.75)	0.4	N(2500,200)
	$450 \leq QL < 700$;	(3.5,3.6,3.7)	0.4	
	$700 \leq QL$	(3.2,3.3,3.8)	0.4	
Supplier 7	$QL < 400$;	(4.2,4.3,4.8)	0.6	N(2500,200)
	$400 \leq QL < 650$;	(4,4.25,4.5)	0.6	
	$650 \leq QL$	(4,4.1,4.2)	0.6	
Supplier 8	$QL < 500$;	(4.5,4.55,5)	0.5	N(2000,100)
	$500 \leq QL < 700$;	(4,4.55,5.1)	0.5	
	$700 \leq QL$	(4.4,4.45,4.5)	0.5	
Supplier 9	$QL < 250$;	(4,5,6)	0.4	N(2000,100)
	$250 \leq QL < 500$;	(4.75,4.85,4.95)	0.4	
	$500 \leq QL$	(4.6,4.7,4.8)	0.4	
QL: Quantity Level N(μ, σ): Normal Distribution (Mean, Standard Deviation) Tolerance value for Capacity =0.90 Holding cost for period 1: (23,25,27) Holding cost for period 2: (25,26,27) Holding cost for period 3: (26,28,30) Slack value for Holding cost: 10				

Table 5F: Fuzzy Numbers for Late Delivery and Defect Percentage

Suppliers	Late Delivery Percentage			Defect Percentage		
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
Supplier 5	(0.08,0.085,0.09)	(0.05,0.07,0.09)	(0.07,0.08,0.09)	(0.07,0.08,0.09)	(0.05,0.07,0.09)	(0.05,0.07,0.09)
Supplier 6	(0.07,0.08,0.09)	(0.05,0.06,0.07)	(0.06,0.07,0.08)	(0.07,0.08,0.09)	(0.04,0.06,0.08)	(0.04,0.06,0.08)
Supplier 7	(0.07,0.08,0.09)	(0.04,0.05,0.06)	(0.04,0.05,0.06)	(0.05,0.07,0.09)	(0.05,0.07,0.09)	(0.05,0.07,0.09)
Supplier 8	(0.06,0.07,0.08)	(0.05,0.06,0.07)	(0.06,0.07,0.08)	(0.05,0.07,0.09)	(0.04,0.05,0.06)	(0.04,0.06,0.08)
Supplier 9	(0.06,0.07,0.08)	(0.05,0.06,0.07)	(0.05,0.07,0.09)	(0.05,0.06,0.07)	(0.04,0.05,0.06)	(0.05,0.07,0.09)

Table 6F: Slack Values for Late Delivery and Defect Percentage

Suppliers	Slack Values for Late Delivery Percentage			Slack Values for Defect Percentage		
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
Supplier 5	0.01	0.01	0.01	0.01	0.01	0.01
Supplier 6	0.01	0.01	0.01	0.02	0.01	0.01
Supplier 7	0.02	0.01	0.02	0.01	0.01	0.02
Supplier 8	0.02	0.01	0.01	0.02	0.01	0.01
Supplier 9	0.02	0.02	0.01	0.03	0.01	0.02

Table 7F: Maximum Truck Numbers for Periods

Trucks / Suppliers	Truck 1			Truck 2			Truck 3		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
Supplier 5	15	18	19	16	15	14	13	13	14
Supplier 6	13	15	14	14	14	13	13	12	13
Supplier 7	12	14	15	13	13	13	12	13	12
Supplier 8	13	14	14	13	14	13	12	12	13
Supplier 9	14	13	15	13	15	12	12	13	14
P1:Period 1, P2: Period 2, P3: Period 3.									

Table 8F: Transportation Cost

Suppliers	Truck 1		Truck 2		Truck 3	
	Transportation Cost	Slack Value for Cost	Transportation Cost	Slack Value for Cost	Transportation Cost	Slack Value for Cost
Supplier 5	(50,51,52)	5	(56,58,60)	6	(60,62,64)	7
Supplier 6	(50,55,60)	5	(55,56,61)	6	(60,65,70)	8
Supplier 7	(50,55,60)	6	(57,58,63)	6	(60,61,62)	7
Supplier 8	(51,54,57)	6	(57,58,59)	7	(65,67,69)	8
Supplier 9	(60,62,64)	4	(62,63,64)	5	(65,67,69)	6
Truck Capacity	60		80		100	

Table 9F: Fuzzy and Stochastic Goals for Company AB

Goals and Demand	Fuzzy and Stochastic Values
Stochastic Goal for Purchasing Cost	N(100000,5000)
Stochastic Goal for Late Delivered Units	N(340,100)
Stochastic Goal for Defective Units	N(400,100)
Fuzzy Goal for Qualitative Aspects	FG(7500,6000)
Demand (Period 1, Period 2 and Period 3)	N(2000,500), N(2000,500), N(2000,500)
N(μ,σ): Normal Distribution (Mean, Standard Deviation) FG: Fuzzy Goal (g_l,LW_l) δ_r for stochastic goals: 0.05 β_r for stochastic goals: 0.10 Tolerance value for Demand =0.90	

Table 10F: Linguistic Weights of Qualitative Criteria for Bundling Discount Problem

Managers	**Criteria** / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Financial Manager	Financial Position	-	EI	MI	I	I	EI
	Volume Flexibility		-	EI	EI	EI	EI
	Technological Capability			-	I	EI	EI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Financial Position	-	I	I	EI	MI	I
	Volume Flexibility		-	MI	EI	MI	I
	Technological Capability			-	MI	MI	EI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-
	Criteria / **Criteria**	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Planning Manager	Financial Position	-	I	MI	EI	I	MI
	Volume Flexibility		-	EI	I	MI	EI
	Technological Capability			-	I	EI	MI
	Reputation				-	EI	MI
	Compliance with Sectoral Price					-	MI
	Communication Issues						-

	Criteria / Criteria	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Quality Manager	Financial Position	-	MI	I	I	MI	I
	Volume Flexibility		-	MI	MI	MI	MI
	Technological Capability			-	MI	EI	EI
	Reputation				-	EI	EI
	Compliance with Sectoral Price					-	EI
	Communication Issues						-
Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.							

Table 11F: Linguistic Scores of Suppliers under Criteria for Bundling Discount Problem

Managers	Criteria / Suppliers	Financial Position	Volume Flexibility	Technological Capability	Reputation	Compliance with Sectoral Price	Communication Issues
Financial Manager	Supplier 1	H	M	H	M	H	VL
	Supplier 2	M	L	H	H	M	VL
	Supplier 3	H	H	M	M	H	VL
	Supplier 4	M	H	H	H	L	VL
	Supplier 5	H	M	M	H	H	VL
	Supplier 6	H	H	M	H	M	VL
	Supplier 7	H	M	H	H	M	VL
	Supplier 8	M	H	H	M	H	VL
	Supplier 9	H	H	H	H	H	VL
	Supplier 10	M	H	M	M	H	VL
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Purchasing Manager	Supplier 1	VH	M	VH	H	VH	VL
	Supplier 2	H	L	H	H	H	VL
	Supplier 3	H	H	H	H	H	VL
	Supplier 4	H	H	VH	H	H	L
	Supplier 5	VH	M	H	VH	H	L
	Supplier 6	H	H	H	VH	H	L
	Supplier 7	VH	M	H	H	H	L
	Supplier 8	H	H	H	H	VH	VL
	Supplier 9	H	H	VH	H	VH	VL
	Supplier 10	M	H	H	H	VH	VL
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**

Planning Manager	Supplier 1	M	H	H	H	VH	L
	Supplier 2	H	M	M	VH	H	VL
	Supplier 3	M	M	H	H	H	VL
	Supplier 4	H	H	H	M	M	VL
	Supplier 5	H	M	H	H	H	L
	Supplier 6	M	H	M	H	H	L
	Supplier 7	H	H	M	H	H	L
	Supplier 8	M	H	H	H	M	VL
	Supplier 9	H	H	M	M	VH	M
	Supplier 10	H	M	H	H	H	VL
	Criteria / Suppliers	**Financial Position**	**Volume Flexibility**	**Technological Capability**	**Reputation**	**Compliance with Sectoral Price**	**Communication Issues**
Quality Manager	Supplier 1	M	H	H	H	H	L
	Supplier 2	M	H	H	VH	H	L
	Supplier 3	M	H	H	H	H	L
	Supplier 4	M	VH	VH	VH	M	L
	Supplier 5	M	H	H	H	H	M
	Supplier 6	VH	H	M	VH	H	M
	Supplier 7	H	H	H	H	H	M
	Supplier 8	H	VH	H	H	H	L
	Supplier 9	VH	VH	H	H	H	L
	Supplier 10	M	VH	H	H	H	L
Very High: VH; High: H; Medium: M; Low: L; Very Low: VL.							

Table 12F: Linguistic Weights of Objective Functions for Bundling Discount Problem

Managers	Objective Functions / Objective Functions	Total Cost	Late Delivery Percentage	Defect Percentage	Qualitative Aspects
Financial Manager	Total Cost	-	MI	MI	EI
	Late Delivery Percentage		-	MI	I
	Defect Percentage			-	I
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Purchasing Manager	Total Cost	-	MI	EI	EI
	Late Delivery Percentage		-	MI	MI
	Defect Percentage			-	MI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Planning Manager	Total Cost	-	EI	EI	EI
	Late Delivery Percentage		-	EI	I
	Defect Percentage			-	EI
	Qualitative Aspects				-
	Objective Functions / Objective Functions	**Total Cost**	**Late Delivery Percentage**	**Defect Percentage**	**Qualitative Aspects**
Quality Manager	Total Cost	-	I	I	MI
	Late Delivery Percentage		-	EI	MI
	Defect Percentage			-	MI
	Qualitative Aspects				-

Extremely Important: EXI; Very Important: VI; Important: I; Moderately Important: MI; Equal Important: EI.

Table 13F: Purchasing Price and Capacity of Suppliers

Products	Suppliers	Purchasing Price ($)	Slack Values	Capacity
Product 1	Supplier 1	(3.5,4,4.5)	0.2	N(2500,200)
	Supplier 3	(2,2.5,3)	0.3	N(2500,100)
	Supplier 8	(3,3.5,4)	0.3	N(2000,100)
	Supplier 9	(2.5,3,3.5)	0.4	N(4000,300)
	Supplier 10	(3,4,5)	0.5	N(3000,400)
Product 2	Supplier 1	(2.1,2.75,3.4)	0.25	N(2500,300)
	Supplier 3	(2,2.5,3)	0.4	N(2000,200)
	Supplier 8	(2.5,3,3.5)	0.3	N(2000,100)
	Supplier 9	(3,3.5,4)	0.5	N(4000,200)
	Supplier 10	(2,2.5,3)	0.5	N(3000,300)
N(μ, σ): Normal Distribution (Mean, Standard Deviation) Tolerance value for Capacity =0.90 Holding cost for product 1 for period 1: (20,21,22) Holding cost for product 1 for period 2: (22,24,26) Holding cost for product 1 for period 3: (20,23,26) Holding cost for product 2 for period 1: (20,22,24) Holding cost for product 2 for period 2: (20,21,22) Holding cost for product 2 for period 3: (20,25,30) Slack Value for Holding cost for product 1 for period 1: 2 Slack Value for Holding cost for product 1 for period 2: 3 Slack Value for Holding cost for product 1 for period 3: 4 Slack Value for Holding cost for product 2 for period 1: 2 Slack Value for Holding cost for product 2 for period 2: 3 Slack Value for Holding cost for product 2 for period 3: 3				

Table 14F: Bundling Conditions

Suppliers	Bundling Condition	Bundling Discount ($)	Slack Values for Bundling Discount
Supplier 1	Product 1>500 and Product 2>100	1.5	0.5
Supplier 3	Product 1>300 and Product 2>200	0.75	0.25
Supplier 8	Product 1>600 and Product 2>100	1	0.5
Supplier 9	Product 1>500 and Product 2>200	0.5	0.2
Supplier 10	Product 1>300 and Product 2>200	1	0.2

Table 15F: Fuzzy Numbers for Late Delivery and Defect Percentage for Products

Products	Suppliers	Late Delivery Percentage			Defect Percentage		
		Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
Product 1	Supplier 1	(0.08,0.085,0.09)	(0.07,0.08,0.09)	(0.05,0.07,0.09)	(0.03,0.05,0.07)	(0.04,0.06,0.08)	(0.04,0.05,0.06)
	Supplier 3	(0.08,0.09,0.1)	(0.06,0.08,0.1)	(0.06,0.07,0.08)	(0.03,0.04,0.05)	(0.03,0.04,0.05)	(0.03,0.04,0.05)
	Supplier 8	(0.06,0.07,0.08)	(0.04,0.06,0.08)	(0.06,0.08,0.1)	(0.04,0.05,0.06)	(0.04,0.05,0.06)	(0.04,0.05,0.06)
	Supplier 9	(0.05,0.07,0.09)	(0.06,0.08,0.1)	(0.06,0.07,0.08)	(0.03,0.04,0.05)	(0.02,0.03,0.04)	(0.02,0.03,0.04)
	Supplier 10	(0.06,0.08,0.1)	(0.06,0.07,0.08)	(0.06,0.08,0.1)	(0.03,0.04,0.05)	(0.03,0.04,0.05)	(0.03,0.04,0.05)

Product 2	Supplier 1	(0.06,0.08,0.1)	(0.06,0.08,0.1)	(0.06,0.07,0.08)	(0.01,0.02,0.03)	(0.02,0.03,0.04)	(0.02,0.03,0.04)
	Supplier 3	(0.06,0.08,0.1)	(0.06,0.08,0.1)	(0.06,0.08,0.1)	(0.02,0.03,0.04)	(0.03,0.04,0.05)	(0.03,0.04,0.05)
	Supplier 8	(0.05,0.06,0.07)	(0.04,0.07,0.1)	(0.06,0.08,0.1)	(0.03,0.04,0.05)	(0.02,0.03,0.04)	(0.02,0.03,0.04)
	Supplier 9	(0.06,0.07,0.08)	(0.05,0.06,0.07)	(0.06,0.07,0.08)	(0.01,0.02,0.03)	(0.02,0.03,0.04)	(0.02,0.03,0.04)
	Supplier 10	(0.05,0.06,0.07)	(0.06,0.07,0.08)	(0.06,0.07,0.08)	(0.02,0.03,0.04)	(0.03,0.04,0.05)	(0.04,0.05,0.06)

Table 16F: Slack Values for Late Delivery and Defect Percentage

Products	**Suppliers**	**Slack Values for Late Delivery Percentage**			**Slack Values for Defect Percentage**		
		Period 1	**Period 2**	**Period 3**	**Period 1**	**Period 2**	**Period 3**
Product 1	Supplier 1	0.035	0.01	0.02	0.01	0.01	0.01
	Supplier 3	0.04	0.02	0.01	0.01	0.01	0.01
	Supplier 8	0.04	0.02	0.01	0.02	0.02	0.02
	Supplier 9	0.04	0.02	0.01	0.01	0.01	0.01
	Supplier 10	0.04	0.02	0.02	0.01	0.01	0.01
Product 2	Supplier 1	0.04	0.01	0.03	0.01	0.01	0.01
	Supplier 3	0.04	0.03	0.01	0.01	0.01	0.01
	Supplier 8	0.04	0.01	0.02	0.01	0.01	0.01
	Supplier 9	0.03	0.02	0.01	0.01	0.01	0.01
	Supplier 10	0.04	0.02	0.02	0.01	0.02	0.01

Table 17F: Maximum Truck Numbers for Product 1 for Periods

Trucks / Suppliers	**Truck 1**			**Truck 2**			**Truck 3**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Supplier 1	15	15	14	17	16	17	15	16	14
Supplier 3	14	16	15	15	15	14	14	14	16
Supplier 8	17	14	14	14	14	16	15	14	14
Supplier 9	14	14	14	15	14	15	14	15	13
Supplier 10	14	13	15	14	16	14	15	15	15
P1;P2;P3:Period 1, Period 2, Period 3									

Table 18F: Maximum Truck Numbers for Product 2 for Periods

Trucks / Suppliers	**Truck 4**			**Truck 5**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
Supplier 1	16	15	16	15	17	14
Supplier 3	15	14	15	15	15	14
Supplier 8	14	15	14	13	13	13
Supplier 9	13	14	14	14	14	15
Supplier 10	13	13	13	14	15	16
P1;P2;P3:Period 1, Period 2, Period 3						

Table 19F: Transportation Cost for Product 1

Suppliers	Truck 1		Truck 2		Truck 3	
	Transportation Cost	**Slack Value for Cost**	**Transportation Cost**	**Slack Value for Cost**	**Transportation Cost**	**Slack Value for Cost**
Supplier 1	(48,50,52)	1	(51,52,53)	1	(50,54,58)	1
Supplier 3	(50,55,60)	1	(56,57,58)	1	(59,60,61)	1
Supplier 8	(50,55,60)	2	(56,57,58)	2	(60,61,62)	2
Supplier 9	(51,54,57)	1	(57,58,59)	1	(60,62,64)	2
Supplier 10	(56,57,58)	1	(56,59,62)	1	(62,63,64)	1
Truck Capacity	60		80		100	

Table 20F: Transportation Cost for Product 2

Suppliers	Truck 4		Truck 5	
	Transportation Cost	**Slack Value for Cost**	**Transportation Cost**	**Slack Value for Cost**
Supplier 1	(38,40,42)	1	(41,42,43)	1
Supplier 3	(40,45,50)	1	(44,47,50)	1
Supplier 8	(43,44,45)	1	(44,47,50)	1
Supplier 9	(44,46,48)	1	(44,48,52)	1
Supplier 10	(45,46,47)	1	(45,49,53)	1
Truck Capacity	100		120	

Table 21F: Fuzzy and Stochastic Goals for Company CD

Goals and Demand	Fuzzy and Stochastic Values
Stochastic Goal for Purchasing Cost	N(65000,7000)
Stochastic Goal for Late Delivered Units	N(550,100)
Stochastic Goal for Defective Units	N(700,200)
Fuzzy Goal for Qualitative Aspects	FG(8000,1000)
Demand (Period 1, Period 2 and Period 3) for product 1	N(2000,100), N(1500,100), N(1000,200)
Demand (Period 1, Period 2 and Period 3) for product 2	N(1200,500), N(1000,500), N(1000,500)
N(μ, σ): Normal Distribution (Mean, Standard Deviation) FG: Fuzzy Goal (g_l,LW_l) δ_r for stochastic goals: 0.05 β_r for stochastic goals: 0.10 Tolerance value for Demand =0.90	